Post - Tensioned Concrete Design

For ACI 318-08

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Post-Tensioned Concrete Design for ACI 318-08

Herein describes in detail the various aspects of the post-tensioned concrete design procedure with the American code ACI 318-08 [ACI 2008]. Various notations used in this chapter are listed in Table 1-1. For referencing to the pertinent sections of the ACI code in this chapter, a prefix “ACI” followed by the section number is used.

1.1 Notations

The following table identifies the various notations used in this chapter.

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Table 1-1 List of Symbols Used in the ACI 318-08 Code

A_{cp}	Area enclosed by the outside perimeter of the section, in^2
A_g	Gross area of concrete, in^2
A_l	Total area of longitudinal reinforcement to resist torsion, in^2
A_o	Area enclosed by the shear flow path, sq-in
A_{oh}	Area enclosed by the centerline of the outermost closed transverse torsional reinforcement, sq-in
A_{ps}	Area of prestressing steel in flexural tension zone, in^2
A_s	Area of tension reinforcement, in^2
A'_s	Area of compression reinforcement, in^2
$A_{s(required)}$	Area of steel required for tension reinforcement, in^2
A_t/s	Area of closed shear reinforcement per unit length of member for torsion, sq-in/in
A_v	Area of shear reinforcement, in^2
A_v/s	Area of shear reinforcement per unit length of member, in^2/in
a	Depth of compression block, in
a_b	Depth of compression block at balanced condition, in
a_{max}	Maximum allowed depth of compression block, in
b	Width of member, in
b_f	Effective width of flange (T-beam section), in
b_w	Width of web (T-beam section), in
b_0	Perimeter of the punching critical section, in
b_1	Width of the punching critical section in the direction of bending, in
b_2	Width of the punching critical section perpendicular to the direction of bending, in
c	Depth to neutral axis, in
c_b	Depth to neutral axis at balanced conditions, in

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Table 1-1 List of Symbols Used in the ACI 318-08 Code

d	Distance from compression face to tension reinforcement, in
d'	Concrete cover to center of reinforcing, in
d_e	Effective depth from compression face to centroid of tension reinforcement, in
d_s	Thickness of slab (T-beam section), in
d_p	Distance from extreme compression fiber to centroid of prestressing steel, in
E_c	Modulus of elasticity of concrete, psi
E_s	Modulus of elasticity of reinforcement, assumed as 29,000,000 psi (ACI 8.5.2)
f'_c	Specified compressive strength of concrete, psi
f'_{ci}	Specified compressive strength of concrete at time of initial prestress, psi
f_{pe}	Compressive stress in concrete due to effective prestress forces only (after allowance of all prestress losses), psi
f_{ps}	Stress in prestressing steel at nominal flexural strength, psi
f_{pu}	Specified tensile strength of prestressing steel, psi
f_{py}	Specified yield strength of prestressing steel, psi
f_t	Extreme fiber stress in tension in the precompressed tensile zone using gross section properties, psi
f_y	Specified yield strength of flexural reinforcement, psi
f_{ys}	Specified yield strength of shear reinforcement, psi
h	Overall depth of a section, in
h_f	Height of the flange, in
ϕM_n^0	Design moment resistance of a section with tendons only, N-mm

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Table 1-1 List of Symbols Used in the ACI 318-08 Code

ϕM_n^{bal}	Design moment resistance of a section with tendons and the necessary mild reinforcement to reach the balanced condition, N-mm
M_u	Factored moment at section, lb-in
N_c	Tension force in concrete due to unfactored dead load plus live load, lb
P_u	Factored axial load at section, lb
s	Spacing of the shear reinforcement along the length of the beam, in
T_u	Factored torsional moment at section, lb-in
V_c	Shear force resisted by concrete, lb
V_{max}	Maximum permitted total factored shear force at a section, lb
V_u	Factored shear force at a section, lb
V_s	Shear force resisted by steel, lb
β_1	Factor for obtaining depth of compression block in concrete
β_c	Ratio of the maximum to the minimum dimensions of the punching critical section
ε_c	Strain in concrete
$\varepsilon_{c,\,max}$	Maximum usable compression strain allowed in extreme concrete fiber (0.003 in/in)
$\varepsilon_{ps\,s}$	Strain in prestressing steel
$\varepsilon_{s,min}$	Strain in reinforcing steel
ε	Minimum tensile strain allowed in steel reinforcement at nominal strength for tension controlled behavior (0.005 in/in)
φ	Strength reduction factor
γ_f	Fraction of unbalanced moment transferred by flexure
γ_v	Fraction of unbalanced moment transferred by eccentricity of shear

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Table 1-1 List of Symbols Used in the ACI 318-08 Code

λ	Shear strength reduction factor for light-weight concrete
θ	Angle of compression diagonals, degrees

1.2 Design Load Combinations

The design load combinations are the various combinations of the load cases for which the structure needs to be designed. For ACI 318-08, if a structure is subjected to dead (D), live (L), pattern live (PL), snow (S), wind (W), and earthquake (E) loads, and considering that wind and earthquake forces are reversible, the load combinations in the following sections may need to be considered (ACI 9.2.1).

For post-tensioned concrete design, the user can specify the prestressing load (PT) by providing the tendon profile. The default load combinations for post-tensioning are defined in the following sections.

1.2.1 Initial Service Load Combination

The following load combination is used for checking the requirements at transfer of prestress forces, in accordance with ACI 318-08 clause 18.4.1. The prestressing forces are considered without any long-term loses for the initial service load combination check.

1.0D + 1.0PT (ACI 18.4.1)

1.2.2 Service Load Combination

The following load combinations are used for checking the requirements of prestress for serviceability in accordance with ACI 318-08 clauses 18.3.3, 18.4.2(b), and 18.9.3.2. It is assumed that all long-term losses have already occurred at the service stage.

1.0D + 1.0PT
1.0D + 1.0L + 1.0PT (ACI 18.4.2(b))

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1.2.3 Long-Term Service Load Combination

The following load combinations are used for checking the requirements of prestress in accordance with ACI 318-08 clause 18.4.2(a). The permanent load for this load combination is taken as 50 percent of the live load. It is assumed that all long-term losses have already occurred at the service stage.

1.0D + 1.0PT 1.0D + 0.5L + 1.0PT	(ACI 18.4.2(b))

1.2.4 Strength Design Load Combination

The following load combinations are used for checking the requirements of prestress for strength in accordance with ACI 318-08, Chapters 9 and 18.

The strength design combinations required for shear design of beams and punching shear require the full PT forces (primary and secondary). Flexural design requires only the hyperstatic (secondary) forces. The hyperstatic (secondary) forces are automatically determined by subtracting out the primary PT moments when the flexural design is carried out.

1.4D + 1.0PT*	(ACI 9.2.1)
1.2D + 1.6L + 1.0PT*	(ACI 9.2.1)
1.2D + 1.6(0.75 PL) + 1.0PT*	(ACI 9.2.1, 13.7.6.3)
0.9D ± 1.6W +1.0PT* 1.2D + 1.0L ± 1.6W + 1.0PT*	(ACI 9.2.1)
0.9D ± 1.0E + 1.0PT* 1.2D + 1.0L ± 1.0E + 1.0PT*	(ACI 9.2.1)
1.2D + 1.6L + 0.5S + 1.0PT* 1.2D + 1.0L + 1.6S + 1.0PT*	(ACI 9.2.1)
1.2D + 1.6S ± 0.8W + 1.0PT* 1.2D + 1.0L + 0.5S ± 1.6W + 1.0PT*	(ACI 9.2.1)
1.2D + 1.0L + 0.2S ± 1.0E + 1.0PT*	(ACI 9.2.1)

* — Replace PT by H for flexural design only

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The IBC 2006 basic load combinations (Section 1605.2.1) are the same. These also are the default design load combinations whenever the ACI 318-08 code is used. The user should use other appropriate load combinations if roof live load is treated separately, or if other types of loads are present.

1.3 Limits on Material Strength

The concrete compressive strength, f'_c, should not be less than 2500 psi (ACI 5.1.1). The upper limit of the reinforcement yield strength, f_y, is taken as 80 ksi (ACI 9.4) and the upper limit of the reinforcement shear strength, f_{yt}, is taken as 60 ksi (ACI 11.5.2).

This procedure enforces the upper material strength limits for flexure and shear design of beams and slabs or for torsion design of beams. The input material strengths are taken as the upper limits if they are defined in the material properties as being greater than the limits. The user is responsible for ensuring that the minimum strength is satisfied.

1.4 Strength Reduction Factors

The strength reduction factors, ϕ, are applied on the specified strength to obtain the design strength provided by a member. The ϕ factors for flexure, shear, and torsion are as follows:

ϕ_t = 0.90 for flexure (tension controlled) (ACI 9.3.2.1)

ϕ_c = 0.65 for flexure (compression controlled) (ACI 9.3.2.2(b))

ϕ = 0.75 for shear and torsion. (ACI 9.3.2.3)

The value of ϕ varies from compression-controlled to tension-controlled based on the maximum tensile strain in the reinforcement at the extreme edge, ε_t (ACI 9.3.2.2).

Sections are considered compression-controlled when the tensile strain in the extreme tension reinforcement is equal to or less than the compression-controlled strain limit at the time the concrete in compression reaches its assumed strain limit of $\varepsilon_{c.max}$, which is 0.003. The compression-controlled strain

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limit is the tensile strain in the reinforcement at the balanced strain condition, which is taken as the yield strain of the reinforcement, (f_y/E) (ACI 10.3.3).

Sections are tension-controlled when the tensile strain in the extreme tension reinforcement is equal to or greater than 0.005, just as the concrete in compression reaches its assumed strain limit of 0.003 (ACI 10.3.4).

Sections with ε_t between the two limits are considered to be in a transition region between compression-controlled and tension-controlled sections (ACI 10.3.4).

When the section is tension-controlled, ϕ_t is used. When the section is compression-controlled, ϕ_c is used. When the section is in the transition region, ϕ is linearly interpolated between the two values (ACI 9.3.2).

1.5 Design Assumptions for Prestressed Concrete

Strength design of prestressed members for flexure and axial loads shall be based on assumptions given in ACI 10.2.

- The strain in the reinforcement and concrete shall be assumed directly proportional to the distance from the neutral axis (ACI 10.2.2).
- The maximum usable strain at the extreme concrete compression fiber shall be assumed equal to 0.003 (ACI 10.2.3).
- The tensile strength of the concrete shall be neglected in axial and flexural calculations (ACI 10.2.5).
- The relationship between the concrete compressive stress distribution and the concrete strain shall be assumed to be rectangular by an equivalent rectangular concrete stress distribution (ACI 10.2.7).
- The concrete stress of $0.85f'_c$ shall be assumed uniformly distributed over an equivalent-compression zone bounded by edges of the cross-section and a straight line located parallel to the neutral axis at a distance $a = \beta c$ from the fiber of maximum compressive strain (ACI 10.2.7.1).

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- The distance from the fiber of maximum strain to the neutral axis, *c* shall be measured in a direction perpendicular to the neutral axis (ACI 10.2.7.2).

Elastic theory shall be used with the following two assumptions:

- The strains shall vary linearly with depth through the entire load range (ACI 18.3.2.1).
- At cracked sections, the concrete resists no tension (ACI 18.3.2.1). Prestressed

concrete members are investigated at the following three stages (ACI 18.3.2):

- At transfer of prestress force
- At service loading
- At nominal strength

The prestressed flexural members are classified as Class U (uncracked), Class T (transition), and Class C (cracked) based on f_t, the computed extreme fiber stress in tension in the precompressed tensile zone at service loads (ACI 18.3.3).

The precompressed tensile zone is that portion of a prestressed member where flexural tension, calculated using gross section properties, would occur under unfactored dead and live loads if the prestress force was not present. Prestressed concrete is usually designed so that the prestress force introduces compression into this zone, thus effectively reducing the magnitude of the tensile stress.

For Class U and Class T flexural members, stresses at service load are determined using uncracked section properties, while for Class C flexural members, stresses at service load are calculated based on the cracked section (ACI 18.3.4).

A prestressed two-way slab system is designed as Class U only with $f_t \le 6\sqrt{f'_c}$ (ACI R18.3.3); otherwise, an over-stressed (O/S) condition is reported.

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The following table provides a summary of the conditions considered for the various section classes.

Assumed behavior	Prestressed			Nonprestressed
	Class U	Class T	Class C	
	Uncracked	Transition between uncracked and cracked	Cracked	Cracked
Section properties for stress calculation at service loads	Gross section 18.3.4	Gross section 18.3.4	Cracked section 18.3.4	No requirement
Allowable stress at transfer	18.4.1	18.4.1	18.4.1	No requirement
Allowable compressive stress based on uncracked section properties	18.4.2	18.4.2	No requirement	No requirement
Tensile stress at service loads 18.3.3	$\le 7.5\sqrt{f'_c}$	$7.5\sqrt{f'_c} < f_t \le 12\sqrt{f'_c}$	No requirement	No requirement

1.6 Serviceability Requirements of Flexural Members

1.6.1 Serviceability Check at Initial Service Load

The stresses in the concrete immediately after prestress force transfer (before time dependent prestress losses) are checked against the following limits:

- Extreme fiber stress in compression: $0.60 f'_{ci}$ (ACI 18.4.1(a))
- Extreme fiber stress in tension: $3\sqrt{f'_{ci}}$ (ACI 18.4.1(b))
- Extreme fiber stress in tension at ends of simply supported members: $6\sqrt{f'_{ci}}$ (ACI 18.4.1(c))

1.6.2 Serviceability Checks at Service Load

The stresses in the concrete for Class U and Class T prestressed flexural members at service loads, and after all prestress losses occur, are checked against the following limits:

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- Extreme fiber stress in compression due to prestress plus total load: $0.60 f_c^{'}$ (ACI 18.4.2(b))

- Extreme fiber stress in tension in the precompressed tensile zone at service loads:

  – Class U beams and one-way slabs: $f_t \le 7.5\sqrt{f'_c}$ (ACI 18.3.3)

  – Class U two-way slabs: $f_t \le 6\sqrt{f'_c}$ (ACI 18.3.3)

  – Class T beams: $7.5\sqrt{f'_c} < f_t \le 12\sqrt{f'_c}$ (ACI 18.3.3)

  – Class C beams: $f_t \ge 12\sqrt{f'_c}$ (ACI 18.3.3)

For Class C prestressed flexural members, checks at service loads are not required by the code. However, 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 ACI 10.6.4 (ACI 18.4.4). It is assumed that the user has checked the requirements of ACI 10.6.4 and ACI 18.4.4.1 to 18.4.4 independently.

1.6.3 Serviceability Checks at Long-Term Service Load

The stresses in the concrete for Class U and Class T prestressed flexural members at long-term service loads, and after all prestress losses occur, are checked against the same limits as for the normal service load, except for the following:

- Extreme fiber stress in compression due to prestress plus total load:

  $0.45 f_c^{'}$ (ACI 18.4.2(a))

1.6.4 Serviceability Checks of Prestressing Steel

Perform checks on the tensile stresses in the prestressing steel (ACI 18.5.1). The permissible tensile stress checks, in all types of

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