5000. Concrete Structures and Construction

- 5100 — Reinforced Concrete
- 5200 — Prestressed Concrete
- 5300 — Reinforcing Bars, Reinforcing Details & Tolerances
- 5400 — Concrete Containments, Modular Construction & Mass Concrete
- 5500 — Durability, NDE & Masonry

5200. Prestressed Concrete

- Objective and Scope
  - Provide introductory level review of analysis and design of prestressed concrete structures
  - Present and discuss
    - Pre and Post Tensioning Systems
    - Introduction to Analysis & design of Prestressed Beams

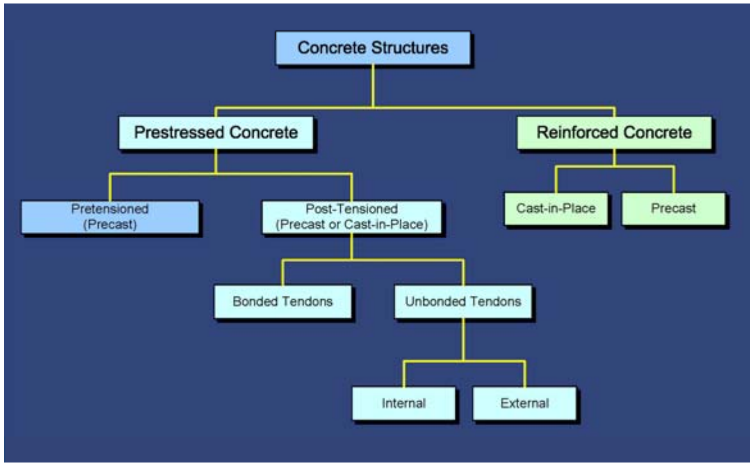
5200. Prestressed Concrete

- 5210 — 5210 - Pre and Post Tensioning Systems
- 5220 — 5220 - Introduction to Analysis & design of Prestressed Beams

5200. Prestressed Concrete

- 5210 — 5210 - Pre and Post Tensioning Systems
- 5220 — 5220 - Introduction to Analysis & design of Prestressed Beams

5210 - Pre and Post Tensioning Systems

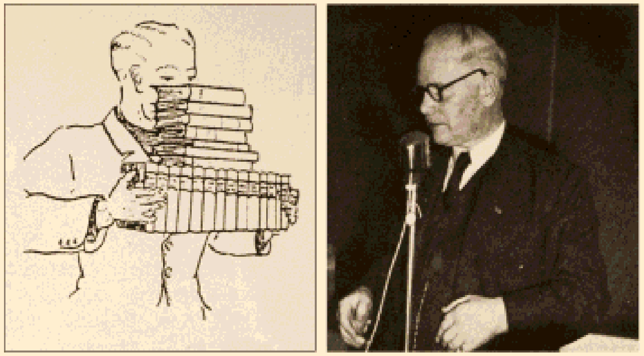


Prestressed Concrete

- What is prestressing?

  Prestressing is a method of reinforcing concrete. The concrete is prestressed to counteract the applied loads during the anticipated service life of the member.

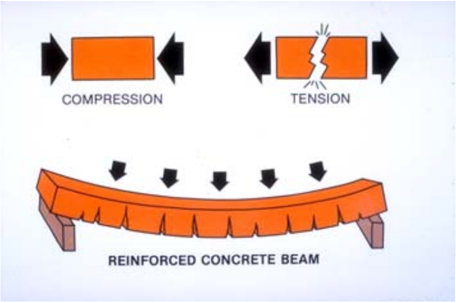
Prestressed Concrete



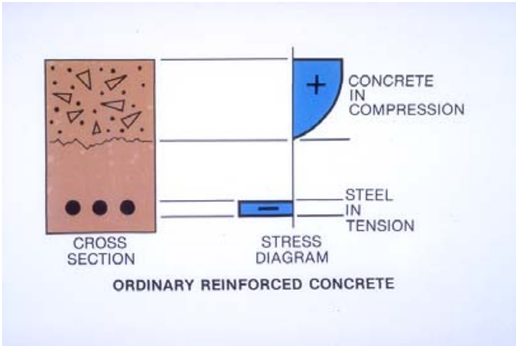
Professor Magnel's explanation of the principle of prestressing.

Professor Magnel teaching prestressed concrete.

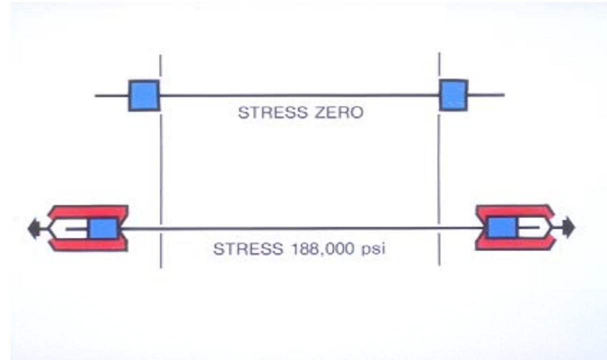
Reinforced Concrete Under Flexural Loading



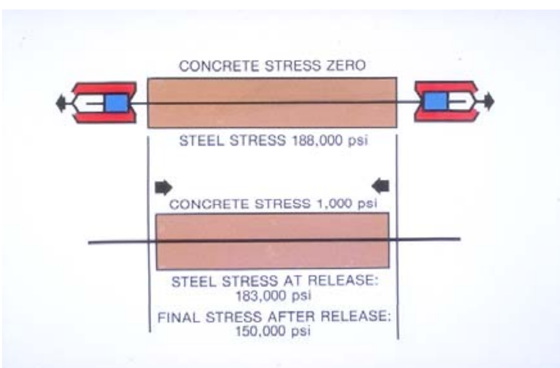
Reinforced Concrete – Cont'd



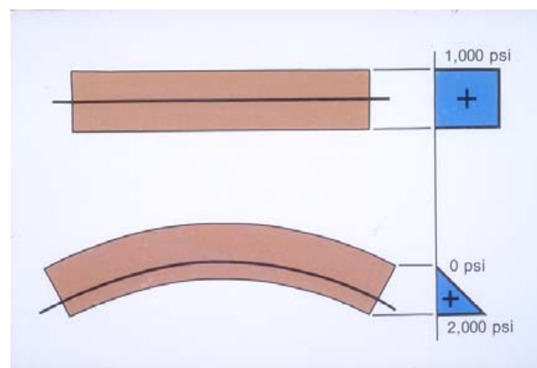
Stress in Prestressed Reinforcement



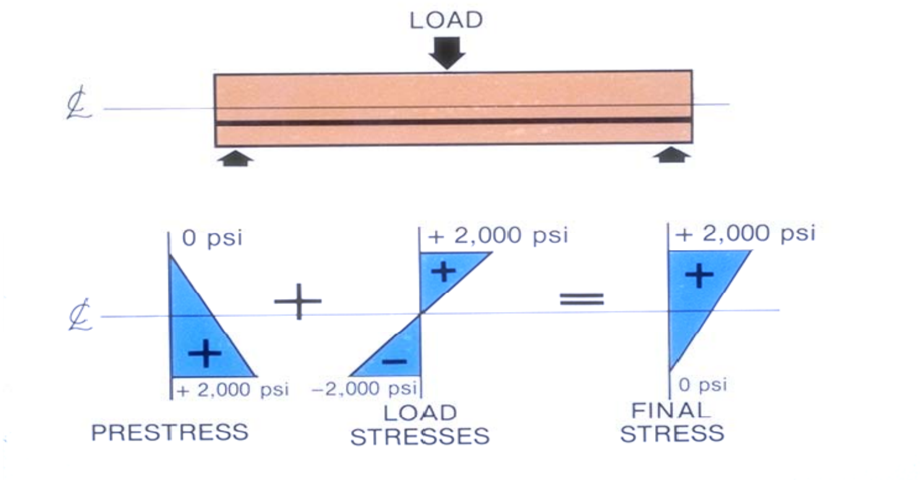
Stress Transfer to Concrete Section



Axially vs Eccentrically Placed Prestressed Reinforcement



Combined Stresses Due to Prestress + External Loading



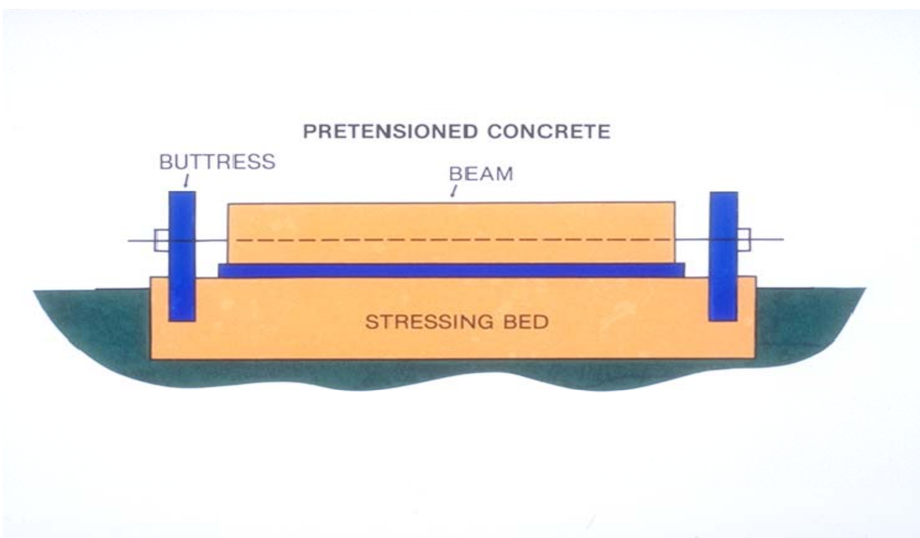
Pre vs Post-Tensioned Concrete

Pre-Tensioning:

Steel tendons are stressed prior to concrete placement, usually at a precast plant remote from the construction site.

Precast, prestressed concrete elements are transported to the construction site.

Pre-Tensioned Concrete



Pre-Tensioning

- The process may involve four steps:
  - (1)Place tendons in some prescribed pattern on the casting bed between two anchorages
    - ACI 18.5.1: Tension not to exceed 94% of the specified yield strength, but not greater than the lesser of 80% of the specified tensile strength of the tendons and the maximum value recommended by the manufacturer of the prestressing tendons or anchorages

Pre-Tensioning (Cont'd)

– (2) Assemble formwork for concrete if not already in place and pour the concrete. Steam curing and high early strength Type III Portland cement may be used to accelerate curing

– (3) The concrete bonds and attains sufficient strength usually within 24 hours at which time the tendons might be cut from their anchorages

Pre-Tensioning (Cont'd)

– (4) The pretensioned member may be removed from the casting bed and placed in storage and later transported to the job site. Only on very large scale projects can the building of a casting yard at the job site be justified

A Pretensioning Plant

A Completed Single T Member being Loaded on a Truck

Post-Tensioned Concrete

Post-Tensioning:

Steel tendons are stressed <u>after</u> the concrete has been placed and gained sufficient strength at the construction site

Post-Tensioning

- Post-tensioning becomes practical when:
  - A structure needs to be fabricated in sections to limit the weight and the sections are joined later by post-tensioning
  - Members are too large to be pretensioned and shipped to the site
  - When a desired cable profile cannot be produced in a pretensioning plant or when the tendons have to be stressed in stages

Post-Tensioning

- Post-tensioning may involve the following four steps:
  - (1) Place flexible hollow metal or plastic tubes at specified locations in the concrete formwork. In some cases the complete tendon assembly including tendons, end plate and anchorage may be placed in the formwork
  - (2) Pour concrete and allow to cure

Post-Tensioning (Cont'd)

- (3) If not already in place, tendons are placed in the tubes and placed in tension by jacking against an abutment or end plate
- (4) Tendons may be bonded or unbonded. If the tendons are to be bonded, pump grout into the tendon tubes. Protective coating may be applied to the end anchorages

History

- The concept of prestressing has been used for centuries
  - Wooden barrels made by tightening metal bands or ropes around barrel staves
- General concepts were first formulated in Germany & the U.S. in the period 1885 – 1890
- Applications were limited because high strength steel was not available
- The first patent for prestressed concrete - P.H. Jackson of San Francisco in 1886

History (Cont'd)

- The theory was further advanced in the early 1900's and linear prestressing of beams, slabs and planks began in Europe about 1928
- Modern development of prestressed concrete attributed to Eugene Freyssinet of France (1928)
- The first major application of linear prestressing in the U.S. was in 1949 – 1950
  - the Walnut Lane Bridge in Philadelphia
- The first post-tensioning in U.S. building construction was in the mid to late 1950s

History (Cont'd)

- In the 1960s, post-tensioned box girder bridges were widely used in California and other Western states
- The use of post-tensioned <u>nuclear containment</u> also began in the 1960s
- The 1970s saw the emergence of new applications
  - Post-tensioned foundations for single and multi-family residences on expansive and compressible soils
  - Prestressed rock and soil anchors

Advantages & Disadvantages

- **Advantages**
  - Smaller members to support the same loads, or same size member can be used for longer spans
  - Crack-free under working loads (prevents water penetration and corrosion, better aesthetics, less maintenance)
  - Total deflections are reduced because of camber produced by prestressing. Also because the full cross-section is crack free and effective, prestressed member tend to have greater stiffness
  - Higher capacity to absorb energy (impact resistance) and high fatigue resistance due to low steel stress variation as a result of the high initial pretension

Advantages & Disadvantages (Cont'd)

- **Disadvantages**
  - Higher strength concrete and steel are required
  - More complicated formwork may be required
  - End anchorages and bearing plates are usually required
  - Closer control required in manufacture and closer control of every phase of construction is required
  - Labor costs are higher
  - Additional conditions must be checked in design, such as stresses when prestressing forces are first applied and stresses after loss of prestress

Post-Tensioning Systems

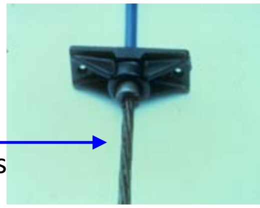
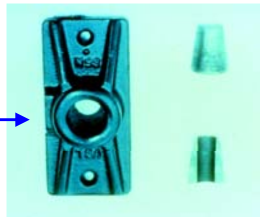
- Three basic types of post-tensioning tendons
  - Unbonded Tendons
    - Standard
    - Encapsulated
  - Bonded Tendons
  - External Tendons

Post-Tensioning Systems

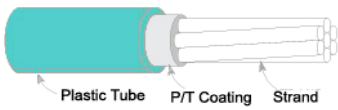
- **Unbonded** single strand tendons are the most widely used in buildings and parking structures


Unbonded Tendon

- A tendon in which the prestressing steel is prevented from bonding, and is free to move, relative to the surrounding concrete
- They consist of 7-wire strands. Most commonly used sizes are 0.5" dia strands
- The prestressing force can only be transferred to the concrete through the anchorage

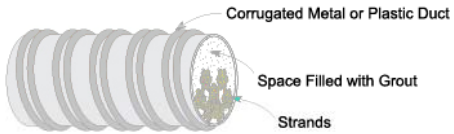



Post-Tensioning Tendons



Unbonded Single Strand Tendon (Plastic Sheath filled with Grease)

Bonded Tendon (Corrugated Sheath Filled with Grout)



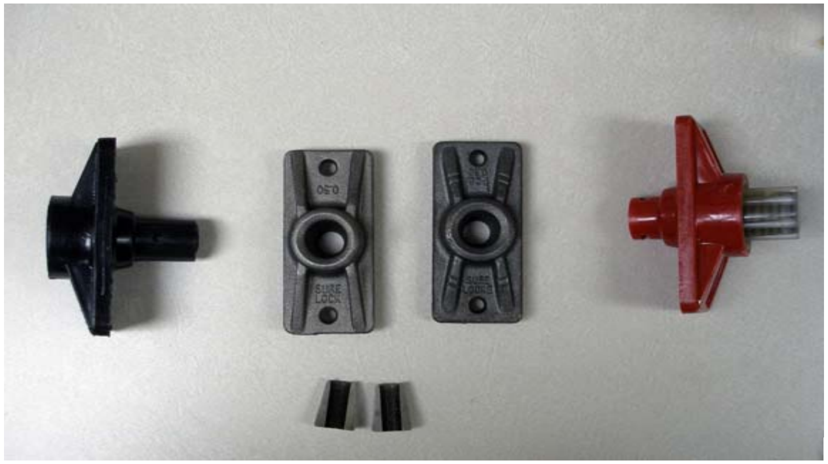
Post-Tensioning Systems - *Unbonded Tendons*

- Single strand
- Extruded plastic sheathing (HDPE or PP)
- Corrosion inhibiting coating (grease or wax)
- Ductile iron anchors & hardened steel wedges
- Supported by chairs and bolsters
- Fully encapsulated in aggressive environments

7-Wire Strand Manufacture

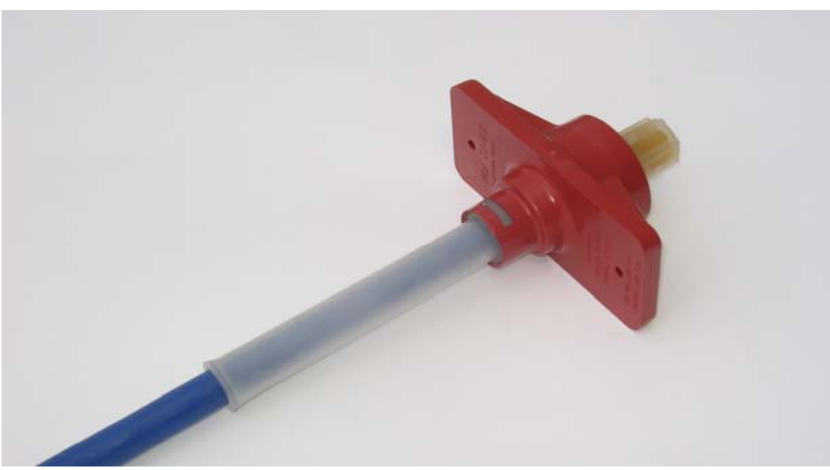
New Strand

Unbonded PT End Anchors



Post-Tensioning Anchors

Encapsulated Tendons

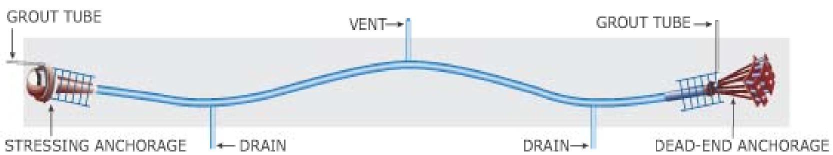


Post-Tensioning Systems - *Bonded Tendons*

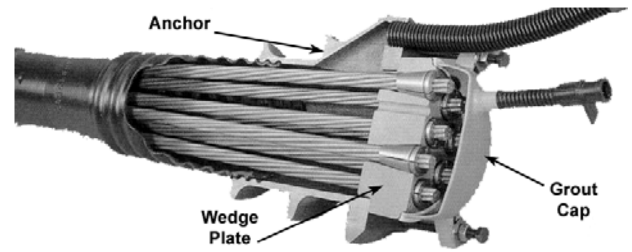
- Strand or bar
- Typically multiple strands
- Steel or plastic duct
- Grouted
- Specially designed anchors

Bonded Tendon

Schematic representation of a typical bonded tendon



Multi-Strand Post-Tensioning Anchor



Duct

- Round, oval, or flat
- Uncoated, galvanized, or coated metal, or various types of plastic
- Minimum Diameter:
  - PTI: 225% of strand cross-section area (250% for Pull-Through Method
  - AASHTO: 250%
  - Single Bar Tendons: Bar diameter + 0.25 in.

Bar Tendon

Multi-Strand Stressing Equipment

- Multi-strand stressing jacks – tend to be heavier and proprietary

Post-Tensioning Systems - *Unbonded vs. Bonded*

- Unbonded
  - Economical
  - Greater layout flexibility
  - Force transmitted solely by the anchors
  - Total force limited by anchor spacing
  - Retrofit openings require more care
  - Replaceable
  - Simple stressing equipment

Post-Tensioning Systems - *Unbonded vs. Bonded (Cont'd)*

- Bonded
  - Can be more costly due to duct placement & grouting
  - Force transmitted by anchors and bond to concrete
  - Greater total force can be applied
  - Strain compatibility with concrete
  - Openings less difficult
  - Minimizes need for non-prestressed reinforcement
  - More complex stressing equipment required

Post-Tensioning Systems - *External Tendons*

- Unbonded bar or strand
- Outside of the concrete structural member
- Straight or harped profile
- Can be grouted, sheathed, encased in grease or wax
- Special case: cable stays

Post-Tensioning Systems - *External Tendons (Cont'd)*

- An external tendon inside a bridge box girder

Tendon Sweep

Post-Tensioning Applications - *Mat Foundations*

Post-Tensioning Applications - *Mat Foundations (Cont'd)*

Unbonded Tendon Layout

Remove Pocket Former

Clean Strands

Mark Tendons

Stress Tendons

- A hydraulic jack pushes directly against an anchorage imbedded in the hardened

Measure Elongation

Burn Tendon Ends

Hydraulic Shear

Clean End Pockets

Patch End Pockets

5200. Prestressed Concrete

5210
- 5210 - Pre and Post Tensioning Systems

5220
- 5220 - Introduction to Analysis & design of Prestressed Beams

5220 - Introduction to Analysis & design of Prestressed Beams

- Chapter 18 and other provisions of the ACI code not specifically excluded (18.1.3) apply to prestressed concrete
- Design Assumptions
  - Section 18.3.3 defines three classes of prestressed flexural members based on f_t (extreme fiber stress in tension in the precompressed tensile zone, computed using gross sectional properties, psi) as follows:

Analysis & Design – Prestressed Concrete (Cont'd)

- Design Assumptions:

(a) Uncracked — Class U: $f_t \leq 7.5\sqrt{f'_c}$

(b) Transition — Class T: $7.5\sqrt{f'_c} < f_t \leq 12\sqrt{f'_c}$

(c) Cracked — Class C: $f_t > 12\sqrt{f'_c}$

Serviceability Design Requirements

Table 24-1 Serviceability Design Requirements (adapted from Table R18.3.3)

	Prestressed			
	Class U	Class T	Class C	Nonprestressed
Assumed behavior	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	$\leq 7.5\sqrt{f'_c}$	$7.5\sqrt{f'_c} < f_t \leq 12\sqrt{f'_c}$	No requirement	No requirement
Deflection calculation basis	9.5.4.1 Gross section	9.5.4.2 Cracked section, bilinear	9.5.4.2 Cracked section, bilinear	9.5.2, 9.5.3 Effective moment of inertia
Crack control	No requirement	No requirement	10.6.4 Modified by 18.4.4.1	10.6.4
Computation of Δf_{ps} or f_s for crack control	–	–	Cracked section analysis	$M/(A_s$ x lever arm), or $0.6f_y$
Side skin reinforcement	No requirement	No requirement	10.6.7	10.6.7

Permissible Stresses in Prestressing Steel

- The permissible tensile stresses in all types of prestressing steel, in terms of the specified minimum tensile strength f_{pu}, are summarized in 18.5.1 as follows:

(a) **Due to tendon jacking force**: …….0.94fpy but not greater than 0.80fpu

Low-relaxation wire and strands ($f_{py} = 0.90f_{pu}$) ………………………….0.80f_{pu}

Stress-relieved wire and strands, and plain bars)(fpy = 0.85fpu)..0.80f_{pu}

Deformed bars (ASTM A722) (fpy = 0.80fpu)…………………………….0.75f_{pu}

Permissible Stresses in Prestressing Steel (Cont'd)

b. **Immediately after prestress transfer**:..0.82fpy but not greater than 0.74fpu

Low-relaxation wire and strands (fpy = 0.90fpu)………………………….. 0.74fpu

Stress-relieved wire and strands, and plain bars (fpy = 0.85fpu) …... 0.70fpu

Deformed bars (fpy = 0.80fpu) ………………………………………………. 0.66fpu

c. **Post-tensioning tendons, at anchorages and couplers, immediately after tendon anchorage** ….. ………………………………………………………….0.70fpu

Loss of Prestress

- The code commentary (Section 18.6) points to several references on how to compute prestress losses
- Formulas are available for calculating
  - Elastic Shortening of Concrete
  - Creep of Concrete
  - Shrinkage of Concrete
  - Relaxation of Tendons

Loss of Prestress (Cont'd)

- Friction Losses
  - Computation of friction losses is covered in ACI 18.6.2. When the tendon is tensioned, the friction losses computed can be checked with reasonable accuracy by comparing the measured tendon elongation and the prestressing force applied by the tensioning jack

Flexural Strength

- Flexural strength of prestressed members is calculated using the same assumptions as non prestressed members
- Flexural strength is defined as ultimate concrete strain of 0.003 and substituting f_{ps} (stress in prestressed reinforcement at nominal strength psi) for f_y
- To avoid lengthy f_{ps} calculations based on strains compatibility, the code provides approximate Equations 18.3, 18.4 and 18.5

Flexural Strength (Cont'd) - Notations

f_{ps} = stress in prestressed reinforcement at nominal strength psi

d_p = distance from extreme compression fiber to centroid of prestressed reinforcement, in.

ρ_p = ratio of prestressed reinforcement = A_{ps} / bd_p

$\omega = \rho f_y / f'_c$

$\omega' = \rho' f_y / f'_c$

f_{pu} = specified tensile strength of prestressing steel, psi

Flexural Strength (Cont'd) - Notations

γ_p = factor for type of prestressing steel

= 0.55 for $f_{py} / f_{pu} \geq 0.80$ (deformed bars)

= 0.40 for $f_{py} / f_{pu} \geq 0.85$ (stress – relieved wire and strands, and plain bars)

= 0.28 for $f_{py} / f_{pu} \geq 0.90$ (low – relaxation wire and strands).

f_{py} = specified yield strength of prestressing steel, psi.

Flexural Strength (Cont'd) – Bonded Tendons

(a) For members with bonded tendons

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

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.

Flexural Strength (Cont'd) – Bonded Tendons

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 $0.15d_p$.

Flexural Strength (Cont'd) – Unbonded Tendons

(b) For members with unbonded tendons and with a span-to-depth ratio of 35 or less:

$$f_{ps} = f_{se} + 10{,}000 + \frac{f_c'}{100\rho_p} \quad (18\text{-}4)$$

but f_{ps} in Eq. (18-4) shall not be taken greater than the lesser of f_{py} and $(f_{se} + 60{,}000)$.

Flexural Strength (Cont'd) – Bonded Tendons

(c) For members with unbonded tendons and with a span-to-depth ratio greater than 35:

$$f_{ps} = f_{se} + 10{,}000 + \frac{f'_c}{300\rho_p} \qquad (18\text{-}5)$$

but f_{ps} in Eq. (18-5) shall not be taken greater than the lesser of f_{py} and **(f_{se} + 30,000)**.

Flexural Strength (Cont'd) – Bonded Tendons

For fully prestressed members Eq. 18 – 3 reduces to:

$$f_{ps} = f_{pu}\left[1 - \frac{\gamma_p}{\beta_1}\rho_p\frac{f_{pu}}{f'_c}\right]$$

Flexural Strength (Cont'd)

With the value of f_{ps} known, the nominal moment strength of a rectangular section or a flanged section where the stress block is within the compression flange, can be calculated as follows:

$$M_n = A_{ps}f_{ps}\left(d_p - \frac{a}{2}\right) = A_{ps}f_{ps}\left(d_p - 0.59\frac{A_{ps}f_{ps}}{bf'_c}\right)$$

where a = the depth of the equivalent rectangular stress block = $\frac{A_{ps}f_{ps}}{0.85bf'_c}$

Limits for Reinforcement of Flexural Members (ACI 18.8)

- The classifications of tension-controlled, transition, or compression controlled and the appropriate ϕ factors also apply to prestressed concrete
- The code provides in Section 18.8.2 provisions analogous to 10.5 for non prestressed members, to ensure adequate cracking and significant deflections before failure
- The code requires adequate reinforcement to develop a design moment strength at least equal to 1.2 times the cracking moment strength

Limits for Reinforcement of Flexural Members (ACI 18.8) (Cont'd)

- Adequate reinforcement to develop a design moment strength at least equal to 1.2 times the cracking moment strength, that is,

$$\phi M_n \geq 1.2\ M_{cr}$$

  where M_{cr} is computed by elastic theory using a modulus of rupture equal to 7.5 $\sqrt{f'_c}$
- The provision of 18.8.2 is waived (based on experience) 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

Stress Conditions for Evaluating Cracking Moment Strength - Notations

A_{ps} = area of prestressed reinforcement in tensile zone

A_c = area of precast member

S_b = section modulus for bottom of precast member

S_c = section modulus for bottom of composite member

P_{se} = effective prestress force

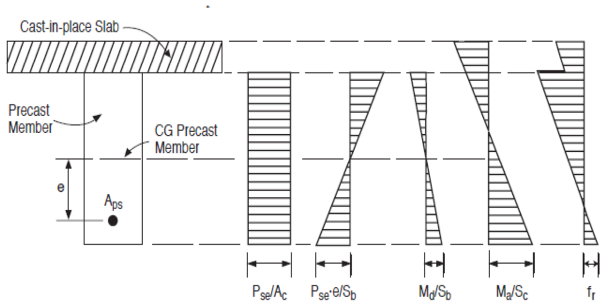
e = eccentricity of prestress force

M_d = dead load moment of composite member

M_a = additional moment to cause a stress in bottom fiber equal to modulus of rupture f_r

Cracking Moment

The cracking moment M_{cr} for a prestressed member is determined by summing all the moments that will cause a stress in the bottom fiber equal to the modulus of rupture f_r. Referring to the figure shown below for an unshored prestressed composite member and taking compression as negative and tension as positive:



Cracking Moment (Cont'd)

$$M_{cr} = \left(f_r + \frac{P_{se}}{A_c} + \frac{P_{se} e}{S_b} \right) S_c - M_d \left(\frac{S_c}{S_b} - 1 \right)$$

For a prestressed member alone (without composite slab), $S_c = S_b$. Therefore, M_{cr} reduces to

$$M_{cr} = \left(f_r + \frac{P_{se}}{A_c} \right) S_b + P_{se} e$$

Minimum Bonded Reinforcement

- The A minimum area of bonded reinforcement shall be provided in all flexural members with unbonded tendons as required by 18.9.2 and 18.9.3.
- Except as provided in 18.9.3, minimum area of bonded reinforcement shall be computed by

$$A_s = 0.004A_{ct} \qquad (18\text{-}6)$$

where A_{ct} is area of that part of cross section between the flexural tension face and center of gravity of gross section

Prestressed Compression Members

- Provisions are same as nonprestressed members
- Prestressing strains have to be accounted for compression members with an average concrete stress due to prestressing of less than 225 psi, minimum nonprestressed reinforcement must be provided (18.11.2.1)
- For compression members with an average concrete stress due to prestressing equal to or greater than 225 psi, 18.11.2.2 requires that all prestressing tendons be enclosed by spirals or lateral ties, except for walls

Prestressed Compression Members (Cont'd)

- Since columns are primarily compression members, creating additional compression by prestressing will not be desirable in most cases
- Columns in some exceptional cases are prestressed when buckling strongly influences the mode of failure. Prestressing is sometimes used on long slender columns that carry large bending moment and small axial load to eliminate cracking so that the whole cross section will be available to resist bending, ie, P-delta effect is decreased and axial capacity of column is increased

Prestressed Compression Members (Cont'd)

- Prestressing may also be used to neutralize dead weight tensile stresses and there by prevent damage of slender precast members during construction

- Prestressing of piles prevents damage during the driving operation. Prestressing prevents damage from transient-tensile stresses generated by the stress waves from impact with the pile driver hammer

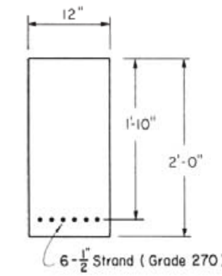
Shear Strength for Prestressed Members (ACI 11.1)

- The design of shear reinforcement for prestressed members is the same as for reinforced nonprestressed concrete members, except that V_c is computed differently and another minimum shear reinforcement requirement applies (11.4.6.4)
- The code permits a slightly wider spacing of (3/4)h (instead of d/2) for prestressed members, because the shear crack inclination is flatter in prestressed members

Example—Flexural Strength of a Prestressed Member

Problem

Calculate the nominal moment strength of the prestressed member shown



f_c' = 5000 psi
f_{pu} = 270,000 psi (low-relaxation strands; f_{py} = 0.90fpu)

Example—Flexural Strength of a Prestressed Member

Solution

- Calculate stress in prestressed reinforcement at nominal strength using approximate value for fps. For a fully prestressed member, Eq. (18-3) reduces to:

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta_1}\rho_p\frac{f_{pu}}{f_c'}\right)$$

$$= 270\left(1 - \frac{0.28}{0.80} \times 0.00348 \times \frac{270}{5}\right) = 252 \text{ ksi}$$

where

$$\gamma_p = 0.28 \text{ for } \frac{f_{py}}{f_{pu}} = 0.90 \text{ for low-relaxation strand}$$

$$\beta_1 = 0.80 \text{ for } f_c' = 5000 \text{ psi}$$

$$\rho_p = \frac{A_{ps}}{bd_p} = \frac{6 \times 0.153}{12 \times 22} = 0.00348$$

Example—Flexural Strength of a Prestressed Member

Solution (Cont'd)

- Calculate nominal moment strength
  - Compute the depth of the compression block:

$$a = \frac{A_{ps}f_{ps}}{0.85bf_c'} = \frac{0.918 \times 252}{0.85 \times 12 \times 5} = 4.54 \text{ in.}$$

$$M_n = A_{ps}f_{ps}\left(d_p - \frac{a}{2}\right)$$

$$M_n = 0.918 \times 252\left(22 - \frac{4.54}{2}\right) = 4565 \text{ in-kips} = 380 \text{ ft-kips}$$

Example—Flexural Strength of a Prestressed Member

Solution (Cont'd)

- Check if tension controlled

$$c/d_p = (a/\beta_1)/d_p = \left(\frac{4.54}{0.80}\right)/22$$

$$c/d_p = 0.258 < 0.375$$

$$\text{Tension controlled} \quad \phi = 0.9$$

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Problem

The rectangular beam section shown below is reinforced with a combination of prestressed and nonprestressed strands. Calculate the nominal moment strength using the strain compatibility (moment-curvature) method.

$f_c{}'$ = 5000 psi

f_{pu} = 270,000 psi (low-relaxation strand; $f_{py} = 0.9f_{pu}$)

E_{ps} = 28,500 ksi

jacking stress = $0.74f_{pu}$

Assume calculated losses = 31.7 ksi

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution

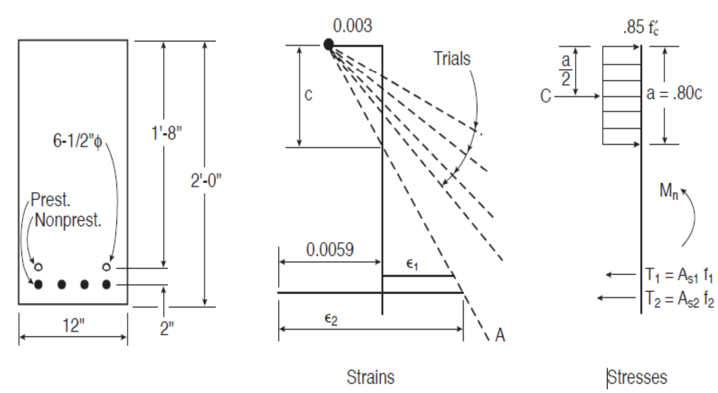
- Calculate effective strain in prestressing steel

$\varepsilon = (0.74f_{pu} - \text{losses})/E_{ps} = (0.74 \times 270 - 31.7)/28{,}500 =$ 0.0059

- Draw strain diagram at nominal moment strength, defined by the maximum concrete compressive strain of 0.003 and an assumed distance to the neutral axis, c. For $f_c{}'$ = 5000, β_1 = 0.80 (see Figure, next slide)

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont'd)



Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont’d)

- Obtain equilibrium of horizontal forces

  The “strain line” drawn above from point 0 must be located to obtain equilibrium of horizontal forces:

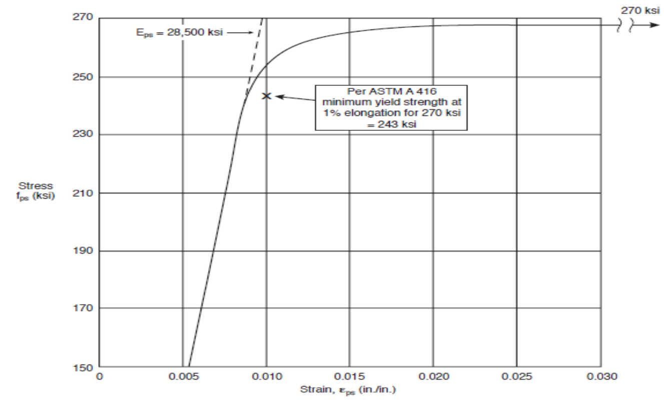
  $$C = T_1 + T_2$$

  To compute T_1 and T_2, strains ε_1 and ε_2 are used with the stress-strain relation for the strand to determine the corresponding stresses f_1 and f_2 (see Figure, next slide). Equilibrium is obtained using an iterative procedure

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont’d)

Stress-Strain Curve for Grade 270, Low Relaxation Strand



The above curve can be approximated by the following equations: $\varepsilon_{ps} \le 0.0086$: $f_{ps} = 28{,}500\, \varepsilon_{ps}$ (ksi)

$\varepsilon_{ps} > 0.0086$: $f_{ps} = 270 - \dfrac{0.04}{\varepsilon_{ps} - 0.007}$ (ksi)

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont’d)

- Equilibrium is obtained using the following iterative procedure
  - a. Assume c (location of neutral axis)
  - b. Compute ε_1 and ε_2
  - c. Obtain f_1 and f_2 from the equations at the bottom of stress – strain figure (previous slide)
  - d. Compute $a = \beta_1 c$
  - e. Compute $C = 0.85\, f_c' ab$
  - f. Compute T_1 and T_2

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont’d)

g. Check equilibrium using $C = T_1 + T_2$

h. If $C < T_1 + T_2$, increase c, or vice versa and return to step b of this procedure. Repeat until satisfactory convergence is achieved.

Estimate a neutral axis location for first trial. Estimate stressed strand at 260 ksi, unstressed strand at 200 ksi.

$T = \Sigma A_{ps} f_s = 0.306\,(200) + 0.612\,(260) = 220$ kips = C

a = C/(0.85 ›b) = 220/(0.85 5 12) = 4.32 in.

$c = a/\beta 1 = 4.32/0.80 = 5.4$ in. Use c = 5.4 in. for first try

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont'd)

- The following table summarizes the iterations required to solve this problem:

Trial No.	c in.	ε_1	ε_2	f_1 ksi	f_2 ksi	a in.	C kips	T_1 kips	T_2 kips	$T_1 + T_2$ kips
1	5.4	0.0081	0.0151	231	265	4.32	220	71	162	233
2 O.K.	5.6	0.0077	0.0147	220	265	4.48	228.5	67	162	229

Example—Flexural Strength of Prestressed Member Based on Strain Compatibility

Solution (Cont'd)

- Calculate nominal moment strength

Using C = 228.5 kips, T_1 = 67 kips and T_2 = 162 kips, the nominal moment strength can be calculated as follows by taking moments about T_2:

$$M_n = \{[(d_2 - a/2)\ C] - [(d_2 - d_1)\ T_1]\}/12 = \{[(22 - (4.48/2)\ 228.5] - [(22 - 20)\ 67]\}/12 = 365 \text{ ft-kips}$$

5200. Prestressed Concrete

- Objective and Scope Met
  - Provideed introductory level review of analysis and design of prestressed concrete structures
  - Presented and discussed
    - Pre and Post Tensioning Systems
    - Introduction to Analysis & design of Prestressed Beams