At the end of this program you should have an understanding of:

- PT technology including PT materials, components, systems, applications, fabrication, installation, stressing, and finishing of tendons.
- Basic steps of analysis and design of building structures including load balancing, secondary moments, prestress losses, and recent code requirements pertaining to PT.
- Recognize common constructability issues and solutions.
Post-Tensioning Institute (PTI)

- A non-profit organization for the advancement of prestressed post-tensioned concrete
- Established in 1976

Activities
- Technical Committees
- Industry Standards and other technical documents
- Dissemination of technical information
- Plant Certification
- Field Personnel Certification
- PT Convention and Technical Sessions
- Research projects and scholarships

INTRODUCTION

- Prestressed Concrete
- Advantages of Post-Tensioning (PT)
- Bonded and Unbonded PT
- PT Applications
- Two-Way Slabs
- One-Way Systems
**Structural Material Types**

- Structural Steel
- Prestressed Concrete
- Reinforced Concrete
  - Pre-Tensioned
    - Bonded Strands
  - Post-Tensioned
    - Bonded Tendons
    - Unbonded Tendons
      - Internal
      - External

**Methods of Prestressing**

- **Prestressing**: Concrete pre-compressed before loading in bending (flexural tension)

1. **Pre-Tensioning**: Steel tensioned *before* concrete is placed (typically precast)
2. **Post-Tensioning**: Steel tensioned *after* concrete is placed and hardened (typically cast-in-place)

Prestressing is **ACTIVE** – can prevent cracks from forming
1. Tension Strands
2. Cast Concrete – Bond strands to concrete
3. Cut Strands – Transfer force to concrete

PRE-TENSIONING

1. Cast Concrete with Duct
2. Feed Strands through Duct
3. Tension Strands
4. Grout Duct (or other corrosion protection)

POST-TENSIONING

Section
Pre-Tensioning

- Force Transfer by Steel-Concrete bond

Post-Tensioning

- Force Transfer at end anchor

Strain Compatibility and Force Equilibrium:

Steel held at length longer than it originally was: **Tension**

Concrete compressed shorter than it originally was: **Compression**

Reinforcement is **PASSIVE**

Nonprestressed reinforcement is fully engaged only after the concrete cracks. It does not prevent cracking but it keeps cracks smaller and distributed.
Reinforced Concrete

CROSS SECTION

STRESS DIAGRAM

ORDINARY REINFORCED CONCRETE

NON-PRESTRESSED REINFORCEMENT VS. POST-TENSIONING

TENSION

REINFORCING BARS

TENSION

TENSION

TENSION

TENSION
SIMPLE PRESTRESSED BEAM

Beam Prestressed and Loaded

SIMPLE PRESTRESSED BEAM

Beam Prestressed and Loaded
BEAM WITH PARABOLIC TENDON

Prestressed beam with parabolic tendon.

BEAM WITH HARPED TENDON

Freebody of Concrete, with Tendon Replaced by Forces
TENDON CONFIGURATION

- Constant
- Harped
- Parabolic

Axially- vs. Eccentrically-Placed Prestressed Reinforcement

- 1,000 psi
- 0 psi
- 2,000 psi
Combined Stresses Due to Prestress + External Loading

LOAD

PRESTRESS

LOAD STRESSES

FINAL STRESS

EXTRUSION PROCESS

Cooling Trough

Extruder

Grease Injector

Bare Strand

Extruded Strand

Plastic Hopper
FABRICATION

- Cutting of tendons to length

FIXED-END ANCHOR

Pull Installation

Push Installation
SHIPPING OF TENDONS

APPLICATIONS
Mixed Use Buildings
Design of Post-Tensioning Building Structures

Residential & Office Buildings

Transfer Girders

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Podium Slabs

Parking Structures
Long Cantilevers

Geometric Flexibility
Slabs-on-Ground

- Residential-Light Commercial
  - Ribbed foundations
  - Uniform thickness foundations
- Industrial floors
Bridges

Storage Tanks
Rehabilitation

Ground Anchors
Two-Way Slabs

- Two-way framing action
- Spans typically up to 40 ft (12.2 m) each direction
- Resists lateral loads by frame action
- Can have capitals, drop panels, beams & joist
- Efficient, least depth & material use

Typically up to 30 ft (9.1 m)

Flat Plates (Two-Way)
Two-way Slabs

Column Cap:
- Extend horizontally from column at least the depth below slab.

Flat Plates with Column Caps (Two-Way)

Typically up to 36 ft (11.0 m)
Two-way Slabs

Drop Panel:
- Extend horizontally from center line column at least 1/6 center line span.
- Project below slab at least 1/4 slab thickness.

Typically up to 40 ft (12.2 m)

Flat Slab w/Drop Panels (Two-Way)

Drop Panels
Band Beams

Typical span dimensions:
- $l_1 = \text{up to 48 ft (14.6 m)}$
- $l = \text{up to 28 ft (6.1 m)}$
- $l_2 = \text{up to 30 ft (9.0 m)}$
- $b = \text{up to 120 in. (3048 mm)}$
- $h = \text{up to 18 in. (460 mm)}$
Band Beams

Beams and One-way Slabs

- One-way framing action
- Beam spans typically up to 65 ft (20 m)
- Slab spans typically up to 30 ft (9.1 m)
- Effective frame action along beam lines
- Clean soffit for mechanical & electrical
Beams and One-way Slabs

Typically up to 65 ft (18.3 m)

Typically up to 30 ft (9.1 m)

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Beams and One-way Slabs

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Beams and One-way Slabs

Typical span dimensions:
- Slab up to 10 ft (3.0 m)
- Joist up to 45 ft (13.7 m)
- Beam up to 35 ft (10.7 m)
- Effective frame action in two directions
Beams and Joists

Typically up to 45 ft (13.7 m)

Joists and Beams (One-Way)

PT BASICS

- Load Balancing
- Secondary Moments
- Preliminary Design
- Hands-on Example
Basic Definitions: Load Balancing

Concept: Portion of dead load is balanced by counter-active forces in post-tensioning tendons

Counter active tendon forces:
- Axial compression + uplift loads
- Balance a portion of the load on the structure

“Removing” post-tensioning tendons from the structure and replacing the tendon’s influence as a series of equivalent loads

Load Balancing

DEAD LOAD

\[ W_{DL} = 100 \text{psf} \ (4.8 \text{ kN/m}^2) \]

POST-TENSIONING

\[ W_{BAL} = 80 \text{psf} \ (3.8 \text{ kN/m}^2) \]

NET LOAD

\[ W_{NET} = 20 \text{psf} + \text{LL} \ (1.0 \text{ kN/m}^2 + \text{LL}) \]

ONLY \( W_{NET} \) CAUSES BENDING
### Load Balancing

\[ M_1 = P \cdot e = \text{Primary Moment} \]

\[ P = \frac{W_{\text{bal}} \cdot L^2}{8 \cdot e} \]

### Secondary Moments

\[ M_s = \text{Secondary Moment} \]

Developed in post-tensioned concrete members due to prestressing forces

Consequence of constraint by the supports to the free movement of the member

- Only develops in indeterminate members
- Simply supported beams have zero secondary moments

**Significant:** must be accounted for in the design of prestressed concrete indeterminate structures (load factor 1.0 in strength design per ACI 318-14, 5.3.11)
Secondary Moments

\[ M_{bal} = M_1 + M_2 = Pe + M_{sec} \]

- \( M_{bal} \) = Balanced moment by post-tensioning equivalent loads
- Secondary reactions at supports due to prestressing
- Secondary Moments (\( M_2 \)) vary linearly between supports

Tendon Profile

- Drape
- Post-Tensioning Tendon
- Neutral Axis

Continuous Post-Tensioned Beam
NUMERICAL EXAMPLE

Key Concepts

- Secondary Moments
- Equivalent Loads
- Tensile Stress Computation

Two-Span Continuous Beam

- $w = 2.5 \text{ k/ft}$
- $a = 24.18''$
- $e = 7.65''$
- $F = 300 \text{ kips}$
- $11.65''$ CGS of anchors
Design of Post-Tensioning Building Structures

March 12, 2020

2020 EduCode Las Vegas - PTI 33

Cross-Section

Section Properties

- $A = 976 \text{ in}^2$
- $S_T = 10282 \text{ in}^3$
- $S_B = 4918 \text{ in}^3$

Neutral Axis $= 11.65''$

Calculate Secondary Moments

1. 60' 24.18'' 300 kips 4''
2. 60' 4''
3. 60' 4'' 11.65''

65

66
Remove Tendon, Compute Equivalent Loads

\[ W_P = \frac{8F_a}{L^2} = \frac{8 \times 300 \times 24.18}{12 \times 60^2} = 1.343 \text{ k/ft} \]

\[ P_1 = 1.343 \times 30 - 300 \times \frac{7.65}{12 \times 60} = 40.3 - 3.19 = 37.11 \text{ k} \]

\[ P_2 = 1.343 \times 60 + 2 \times 3.19 = 86.96 \text{ k} \]

Replace Tendon with Equivalent Loads

Hole in Concrete
Calculate Reactions to Equivalent Loads

Each Reaction has a two components:

1. Equilibrates the concentrated load
2. Equilibrates the uniform balanced load

\[ R_1 = 37.11 - \frac{3}{8} \times 1.343 \times 60 = 37.11 - 30.22 = 6.89 \, k \]

\[ R_2 = 86.96 - 1.25 \times 1.343 \times 60 = 86.96 - 100.73 = -13.77 \, k \]

Put Tendon Back in Beam

1. 60'
2. 60'
3. 60'

\[ R_1 = 6.89 \, k \]
\[ R_2 = 13.77 \, k \]
\[ R_1 = 6.89 \, k \]
Secondary Reactions and Moments

\[ R_1 = 6.89 \text{k} \quad R_2 = 13.77 \text{k} \quad R_1 = 6.89 \text{k} \]

\[ M_2 = 6.89 \times 60 = 413.4 \text{ ft-kips} \]

The Easy Way

\[ M_2 = M_{bal} - F_e \]

\[ M_2 = \frac{1.343 \times 60^2}{8} - 300 \frac{7.65}{12} \]

\[ = +413.1 \text{ ft-kips} \]
Calculate Maximum Flexural Tensile Stress at Bottom of Beam

Use Equivalent Load Free Body Diagram
Net Load Free Body Diagram

1. 37.11 k
2. 300 k
3. 86.96 k

W_{net} = 2.5 - 1.343 = 1.157 k/ft

W_{net} = 1.157 k/ft

Hole in Concrete
Net Load Shears and Moments

\[ M^+ = \frac{9wl^2}{128} = \frac{9 \times 1.157 \times 60^2}{128} = 292.9 \text{ ft-kips} \]

\[ M^- = \frac{wl^2}{8} = \frac{1.157 \times 60^2}{8} = -520.7 \text{ ft-kips} \]

Maximum Flexural Tensile Stress at Bottom of Beam

Occurs at point of max. positive net moment \((M^+_{\text{net}} = +292.9 \text{ ft-k} @ x=22.5' \text{ from Point A}):\]

\[ f = -\frac{F}{A} + \frac{M_{\text{net}}}{S_B} = -\frac{300}{976} + \frac{292.9 \times 12}{4918} \]

\[ = -0.307 + 0.714 = +0.407 \text{ ksi} \]
EXAMPLE OF A PARKING SLAB

One-Way Slab

- L = 23'-0"
- One-way system
- L/48 = 23 x 12/48
- = 5.75 in.
- Min. thick. = 5 in. (siliceous aggregates)

- Cantilever span = 7'-6"
- L/24 = 7.5 x 12/24
  = 3.75 in.
- Use 6 in. thick slab
**Prestressing Force and Profile**

**Typical Span (Interior)**
- CGS \(\text{Bot} = \frac{3}{4} + \frac{1}{4} = 1\) in.
- CGS \(\text{TOP} = \frac{1}{4} + \frac{1}{4} = 1\frac{1}{2}\) in. (Larger cover at top)
- \(e = 6 - 1 - 1.5 = 3.5\) in.

- DL = 6 x 150/12 = 75 psf + 5 psf finishes
- Balance 70% of DL \(w_{\text{bal}} = 56\) psf
- \(P = \frac{w_{\text{bal}} l^2}{8e}\)
- \(P = 56 \times 23^2/(8 \times 3.5/12) = 12,700\) plf
- Use 13 k/ft of force in interior spans
- 13,000/(6X12) = 180 psi (OK!)

**Left Exterior Span**
- Top CGS = 1\(\frac{1}{4}\) + \(\frac{1}{4}\) = 1\(\frac{1}{2}\) in. (interior support)
- Top CGS = 2.5 in. (exterior support) **Assumed!**
- Bottom cover = 1\(\frac{1}{2}\) + \(\frac{1}{4}\) = 1\(\frac{3}{4}\) in.
- \(e = 6 - ((2.5 + 1.5)/2 + 1.75) = 2.25\) in.
- \(P = 56 \times 23^2/(8 \times 2.25/12) = 19,750\) plf
- Use 20 k/ft
Check Cantilever

Check Cantilever for Overbalance
• \( e = 3 - 2.5 = 0.5 \text{ in.} \)
• \( W_{\text{bal}} = \frac{2 \times 20,000 \times 0.5}{5 \times 5} \)
• \( W_{\text{bal}} = 66.7 \text{ psf} = \frac{w_{\text{bal}}}{w_{DL}} = 66.7/80 \)
  \( = 83\% \text{ OK!} \)
• If overbalanced then revise eccentricity at support and
• Recalculate post-tensioning force in ext. span

Prestressing Force and Profile

Right Exterior Span
• Top Cover = 1¼ + ¼ = 1½ in. (interior support)
• Top Cover = 1.5 in. (exterior support) Assumed!
• Bottom cover = 1½ + ¼ = 1 ¾ in.
• \( e = 6 - ((1.5 + 1.5)/2 + 1.75) \)
  \( = 2.75 \text{ in.} \)
• \( P = 56 \times 23^2/(8 \times 2.75/12) \)
  \( = 16,160 \text{ plf} \)
• Use 16.5 k/ft
Check Cantilever

Check Cantilever for Overbalance

- $e = 3 - 1.5 = 1.5 \text{ in.}$
- $W_{bal} = \frac{2 \times 16,500 \times 1.5}{7.5 \times 7.5}$
- $W_{bal} = 73.3 \text{ psf} = \left(\frac{w_{bal}}{w_{DL}} = \frac{66.7}{80}\right)$
  - $= 91.7\% \text{ OK!}$

- If overbalanced then revise eccentricity at support and
- Recalculate post-tensioning force in ext. span
**ONE-WAY SLAB**

**HANDS ON EXAMPLE**

- Determine the Slab thickness
- Determine the Tendon Profile and Post-Tensioning Forces
- Estimate the Amount of PT Steel in lb/ft²

---

**Determine Thickness**

L = 30’ One Way Slabs L/48

t = 30 \times 12 / 48 = 7.5 \text{ in.} \text{ Use 8” Thick Slab}

DL = 8 / 12 \times 150 = 100 \text{ psf}

Balance 70% of DL = 100 \times 0.7 = 70 \text{ psf}

**Span 1**

\[ e = 8 - (4 + 1) / 2 - 1.75 = 3.75 \text{ in.} \]

\[ P = 70 \times 30^2 / (8 \times 3.75 / 12) = 25.2 \text{ k/ft} \]
One-Way Slab

Hands On Example

**Span 3**

\[ e = \frac{8-(4+1)/2 - 1.75}{2} = 3.75 \text{ in.} \]

\[ W_{bal} = \frac{8 \times 25,200 \times \frac{3.75}{12}}{27^2} = 86.4 \text{ psf OK!} \]

**Span 2**

Balance 100% of DL

\[ e = \frac{W_{bal}l^2}{8P} = \frac{100 \times 15^2}{8 \times 25,200} = 0.11' = 1.34" \]

Use \( e = 1.25" \)

Cover at Mid = 8-1-1.25 = 5.75"

---

**DESIGN STEPS / ANALYSIS**

- Preliminary Design
- Serviceability
- Strength
Planning and Design of PT Systems

- Planning
  - Architectural Criteria
  - Shape, Spans, Occupancy
  - Exposure and Durability Criteria
- General Design Objectives
  - Governing Codes
  - Criteria in Excess of Code

Conceptual Design Phase

- Determine Floor System
- Coordinate Structural Geometry
- Determine Member Sizes
- Determine Loading
  - Dead Load
  - Live Load
  - Lateral Loads (if applicable)
Conceptual Design Phase (Continued)

- Conceptual Design Phase
- Design Development
  - Material and Cross-Sectional Properties
  - Set Design Parameters
- Design and Analysis
  - One-Way Systems
  - Two-Way Systems
- Construction Documents
  - Layout of Reinforcement
  - Drawing and Detailing

Ref: Design of Prestressed Concrete Structures by T.Y. Lin and Ned Burns
STRUCTURAL MODELING TECHNIQUES

Two-Way Slabs

- DO NOT use simplified analysis using coefficients (Direct Design Method)
- DO NOT use middle/column strip concept
- Use the Equivalent Frame Method, EFM, permitted by ACI 318-19 in Sec. 8.2.1; covered in Sec. 8.11 of ACI 318-14, excluding Sec. 8.11.6.5 and 8.11.6.6.
- Apply total tributary width when using EFM
- Finite Element Analysis
Banded Tendons:

- **Span length:** short direction
- **Openings:** tendon path
- **Cantilevers:** distributed tendons
- **Column shape:** as many tendons as possible directly over column

Banded Tendon Direction
Banded / Distributed Tendons in 2-Way Slabs

- PTI Research Project at Virginia Tech (Joined effort PTI – Bekaert)

- Goals:
  - Permit Two-Way Banded PT arrangement
  - Large areas with no PT
  - Remove Sec. 8.7.2.3 from ACI 318

**Design Requirements**

- PT structures are designed to satisfy both serviceability & ultimate limit states

- Service load design entails:
  - Stresses at working loads are within permissible limits
  - Deflections, vibrations, and cambers are acceptable
  - Crack widths are controlled through the use of non-prestressed reinforcement
  - PT tendons are protected against corrosion
Post-Tensioned Reinforcement

- **One-Way Slabs**
  - Provide non-prestressed or prestressed temperature & shrinkage reinforcement (ACI 318-19, Sec. 7.6.4)
  - Typical prestressed (T & S) \( P/A = 100 \text{ psi} \ (0.7 \text{ MPa}) \)

Post-Tensioned Reinforcement

- **Two-Way Slabs**
  - Banded tendons grouped over column lines
  - Distributed tendons uniformly spaced in perpendicular direction
  - Provide 2 continuous strands over columns
    (ACI 318-19, Sec. 8.7.5.6.1)
Nonprestressed Reinforcement

- Provide minimum amount of rebar per ACI 318-19:
  - One-way slabs: Sec. 7.6.2.3 (slabs), 9.6.2.3 (beams)
  - Two-way slabs: Sec. 8.7.5.2

- Add nonprestressed reinforcement per ultimate strength requirements

Minimum Positive Moment Bonded Reinforcement for Two-Way Slabs

- Two-way slabs must be designed as Class U
  - ACI 318-19, 8.6.2.3

Table 8.6.2.3—Minimum bonded deformed longitudinal reinforcement $A_{s,\text{min}}$ in two-way slabs with bonded or unbonded tendons

<table>
<thead>
<tr>
<th>Region</th>
<th>Calculated $f_t$ after all losses, psi</th>
<th>$A_{s,\text{min}}, \text{ in.}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive moment</td>
<td>$f_t \leq 2\sqrt{f_s'}$</td>
<td>Not required</td>
</tr>
<tr>
<td></td>
<td>$2\sqrt{f_s'} &lt; f_t \leq 6\sqrt{f_s'}$</td>
<td>$\frac{N_e}{0.5f_s'}$</td>
</tr>
<tr>
<td>Negative moment at columns</td>
<td>$f_t \leq 6\sqrt{f_s'}$</td>
<td>$0.00075A_{cf}$</td>
</tr>
</tbody>
</table>

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**Minimum Negative Moment Bonded Reinforcement for Two-Way Slabs**

ACI 318-19, 8.6.2.3

\[
As = 0.00075 \, A_{cf}
\]

ACI 318-19, 8.7.5.3

- Placed within 1.5h each side of the column support
- Minimum 4 bars each direction
- Spacing ≤ 12” (305 mm)
- Extend a minimum \( \ell_i/6 \) on each side of support

**Location of Negative Moment Reinforcement**

- Place rebar within an area limited by the column dimension plus 1.5h on each side; ACI 318-19, 8.7.5.3.
- Place distributed tendons (transverse) below the banded tendons
- #4 (#10 M) bars, typical to match tendon diameter
Location of Negative Moment Reinforcement

PRESTRESS LOSSES

Initial Losses
- Friction, \( F \)
- Elastic shortening, \( ES \)
- Anchor set (wedge seating), \( A \)

Long Term Losses
- Concrete shrinkage, \( S \)
- Concrete creep, \( C \)
- Post-tensioning steel relaxation, \( R \)
Friction Losses, F

- Compute force along tendon

\[
\mu = \text{Coefficient of angular friction (see PT Manual Appendix A.1)}
\]
\[
\alpha = \text{Change in angle between force at anchorage and at x, in radians}
\]
\[
k = \text{Wobble coefficient, per unit length (see PT Manual Appendix A.1)}
\]

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Elastic Shortening

\[
ES = 0.5 \frac{E_s}{E_{ci}} f_{cir}
\]

\[
E_s = \text{MOE of Prestressing Steel}
\]
\[
E_{ci} = \text{MOE of Concrete.}
\]
\[
E_{ci} = E_c \left( \frac{\text{days}}{28} \right)^{1/2}
\]
\[
f_{cir} = \text{Concrete stress at the center of gravity of the prestressing steel due to prestressing force and dead load of beam immediately after transfer.}
\]

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Anchor Set at Transfer, A

Wedge Set:

- Wedges move approximately ¼” (6 mm) into anchor wedge cavity to transfer force from jack to anchor
- Wedge set loss may be significant for short unbonded tendons

Steel Wedges

- Lock the strand in the wedge cavity of the anchor after stressing to hold the force
- Made of steel with ductile core to conform to strand shapes; longitudinal cracking is acceptable
- Hardened steel surface with serrated teeth to bite into strand to lock it in elongated state
**Shrinkage**

\[ SH = 8.2 \times 10^{-6} K_{sh} E_s \left( 1 - 0.06 \frac{V}{S} \right) (100 - RH) \]

\[ \frac{V}{S} = \text{Volume to surface ratio} \]

\[ RH = \text{Relative humidity} \]

**Creep**

**Bonded**

\[ CR = K_{cr} \left( \frac{E_s}{E_c} \right) f_{cpru} \]

\[ K_{cr} = 1.6 \text{ (post-tensioned)} \]

\[ f_{cpru} = \text{avg. compressive stress in the concrete at the time immediately after stressing.} \]

**Unbonded**

\[ CR = K_{cr} \left( \frac{E_s}{E_c} \right) (f_{ci} - f_{cds}) \]

\[ K_{cr} = 1.6 \text{ (post-tensioned)} \]

\[ f_{cds} = \text{Stress in concrete due to all superimposed permanent dead loads that are applied to the member after it has been prestressed.} \]
Relaxation

$$RE = \left[ K_{re} - J(SH + CR + ES) \right] C$$

270 Grade Low-lax Strand

$$K_{re} = 5000$$

$$J = 0.040$$

<table>
<thead>
<tr>
<th>$f_{pil}/f_{pu}$</th>
<th>C (Low-lax Strand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>1.28</td>
</tr>
<tr>
<td>0.79</td>
<td>1.22</td>
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<tr>
<td>0.78</td>
<td>1.16</td>
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<td>0.73</td>
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<td>0.61</td>
<td>0.37</td>
</tr>
<tr>
<td>0.60</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Prestress Losses

Diagram showing a structure with labeled points and distances, demonstrating the concept of prestress losses.
Stressing From Both Ends

TENDON ELONGATION

- Use the following formula to calculate the elongation of a tendon:

\[ \Delta = \frac{F_{AVG} \times L}{A \times E} \]

- \( F_{AVG} \) = Prestress force in Kips (Average Force After Friction; (approximately at 70% MPTS)
- \( L \) = Length of the prestressing steel in inches
- \( A \) = Area of the prestressing steel in sq. in.
- \( E \) = Modulus of elasticity of the prestressing steel in ksi
### Stress in Post-Tensioning Steel for Service Load Design

- **Initial prestress:**  \( f_{pi} = f_{pj} - ES - F - A \)
- **Effective prestress:**  \( f_{pe} = f_{pi} - C - S - R \)

Where:
- \( f_{pi} \) = Initial stress in post-tensioning strands
- \( f_{pj} \) = Jacking stress in post-tensioning strands
- \( f_{pe} \) = Effective stress in post-tensioning strands after all losses

**Final Effective Force:** Force in tendon after all initial and long term losses.

---

### Final Effective Force

- **Final Effective Force** in the prestressing steel is calculated by taking into account all **Immediate** and **Long Term Losses**.
- This **force** is typically calculated by the post-tensioning supplier.
- \( F_e \) can be **approximated** to be 65% of Breaking Load.

For ½” grade 270 steel:

\[
270 \text{ ksi} \times 0.153 \text{ in}^2 \times 0.65 = 26.8 \text{ Kips}
\]
**STEP 1 – PRELIMINARY DESIGN**

- Determine structural system (one-way or two-way)
- Coordinate slab spans/column layout with architect
  - Determine slab thickness
  - Note: LL/DL ratio must be < 1.0 to use Table 2.1 of PTI’s “Design of Post-Tensioned Slabs With Unbonded Tendons” publication
- Establish consistent sign convention for gravity loads and primary moment, $P_e$

### Preliminary Design Span/Depth Ratio

<table>
<thead>
<tr>
<th>Floor System</th>
<th>Span/Depth Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-way slabs</td>
<td>48</td>
</tr>
<tr>
<td>Two-way slabs</td>
<td>45</td>
</tr>
<tr>
<td>Two-way slab with drop panel (minimum drop panel L/6 each way)</td>
<td>50</td>
</tr>
<tr>
<td>Two-way slab with two-way beams</td>
<td>55</td>
</tr>
<tr>
<td>Two-way waffle slab (5 ft x 5 ft grid) (1.5 x 1.5 m)</td>
<td>35</td>
</tr>
<tr>
<td>Beams ($b = \frac{b_c}{2}$)</td>
<td>20</td>
</tr>
<tr>
<td>Beams ($b = 3h$)</td>
<td>30</td>
</tr>
<tr>
<td>One-way joists</td>
<td>40</td>
</tr>
</tbody>
</table>

*These values apply for members with LL/DL ratios < 1.0

Source: Design of Post-Tensioned Slabs With Unbonded Tendons; 3rd Ed., PTI
Minimum Slab Thickness
(Governed by Fire Rating, IBC 2015, Table 722.2.1.1)

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>4 hr</th>
<th>3 hr</th>
<th>2 hr</th>
<th>1 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siliceous</td>
<td>7.0 (180)</td>
<td>6.2 (155)</td>
<td>5.0 (125)</td>
<td>3.5 (90)</td>
</tr>
<tr>
<td>Carbonate</td>
<td>6.6 (170)</td>
<td>5.7 (145)</td>
<td>4.6 (115)</td>
<td>3.2 (80)</td>
</tr>
<tr>
<td>Sand Ltwt Conc.</td>
<td>5.4 (135)</td>
<td>4.6 (115)</td>
<td>3.8 (95)</td>
<td>2.7 (70)</td>
</tr>
<tr>
<td>Ltwt Concrete</td>
<td>5.1 (130)</td>
<td>4.4 (110)</td>
<td>3.6 (90)</td>
<td>2.5 (65)</td>
</tr>
</tbody>
</table>

Establish Tendon Profile

Post-Tensioned Reinforcement

- Most buildings are constructed with unbonded tendons
- Use parabolic tendon profile for uniformly loaded beams

- Determine Cover
  - Fire Rating Criteria
  - Durability Considerations
A span is considered to be restrained when it can resist the horizontal forces developed during a fire.

- Typically end bays are considered to be unrestrained unless calculations can show otherwise (ACI 423.3-05)
- Different interpretation of Code: Cast-in-place concrete slab could be considered restrained

---

**Concrete Cover**

(Governed by Fire Rating; IBC 2015)

| Cover Thickness for Fire Endurance – Carbonate and sand-lightweight aggregate concrete - in. (mm) |
|---|---|---|---|---|
| Restrained / Unrestrained | Structure Type | 4 hr | 3 hr | 2 hr | 1 hr |
| Restrained | Solid Slabs | 1 ¼ (32) | 1 (25) | **¾ (19)** | - |
| | Beams & Girders 8” Wide | 2 ½ (63) | 2 (51) | 1 ¾ (44) | - |
| | Beams & Girders > 12” Wide | 2 (51) | 1 ½ (44) | 1 ½ (38) | - |
| Unrestrained | Solid Slabs | - | 2 (51) | **1 ½ (38)** | - |
| | Beams & Girders 8” Wide | 4 ½ (114) | 2 ½ (63) | 1 ¾ (44) | - |
| | Beams & Girders > 12” Wide | 3 (76) | 2 ½ (63) | 2 (51) | 1 ½ (38) |
**Load Balancing**

\[ \mathbf{M}_1 = P \cdot e = \text{Primary Moment} \]

\[ P = \frac{W_{\text{bal}} \cdot l^2}{8 \cdot e} \]

**Preliminary Design of PT**

- Determine Minimum Prestressing
  - One way Slabs/Parking Garages
    - Aggressive environments use 150-200 psi (1.0-1.4 MPa)
    - Normal environment use 125 psi (0.9 MPa)
    - Temperature tendons use 100 psi (0.7 MPa)
  - Two Way Slabs
    - Minimum use 125 psi (0.9 MPa)

- Load Balancing:
  - 60% to 70% of DL for one- and two-way slabs
  - 70% to 80% of DL for beams
  - 100% for spandrel beams supporting ext. cladding
Variations to Estimations

- End bays may require more PT for the same span
- Heavy exterior skin loads that must be supported by the slab
- Parking slab PT quantity will increase due to increased clear cover requirements in aggressive regions

STEP 2 - DETERMINE LOADING

- Dead Loads [from preliminary section thickness]
- Live Loads [IBC: 40 psf (1.9 kN/m²) for parking]
- Lateral Loads [e.g., wind, seismic, etc.]
**STEP 3 – CALCULATE SECTION PROPERTIES**

- Slab section properties
- Column properties
- Drop panel properties for two-way slabs; dimensions per Sec. 8.2.4 apply to nonprestressed slabs only

**STEP 4 – MATERIAL PROPERTIES**

- Slab concrete properties $f'_c$
  - Typically use 5,000 psi (35 MPa) concrete
- Column concrete properties $f'_c$
  - Typically use 5,000 psi (35 MPa) concrete
- Non-prestressed reinforcement properties $f_y$
  - Typically 60 ksi (0.4 MPa) steel
- Post-tensioning reinforcement properties $f_{pu}$
  - Typically 270 ksi (1860 MPa) steel
STEP 5 – SET DESIGN PARAMETERS

- Set allowable stresses (initial and final)
- Set average compression limits
- Set target balanced loading (65% to 85% total DL)
- Set cover requirements for reinforcement
- PT tendons: drape profile, center of gravity
- Set load combinations

Serviceability Requirements

- ACI 318-19, Sec. 24.5.2.1

<table>
<thead>
<tr>
<th>Table R24.5.2.1—Serviceability design requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed behavior</td>
</tr>
<tr>
<td>Section properties for stress calculation at service loads</td>
</tr>
<tr>
<td>Allowable stress at transfer</td>
</tr>
<tr>
<td>Allowable compressive stress based on cracked section properties</td>
</tr>
<tr>
<td>Tensile stress at service loads</td>
</tr>
<tr>
<td>Deflection calculation basis</td>
</tr>
<tr>
<td>Crack control</td>
</tr>
<tr>
<td>Computation of $\Delta_{cr}$ or $f_c$ for crack control</td>
</tr>
<tr>
<td>Slab skin reinforcement</td>
</tr>
</tbody>
</table>

* $\leq 0.025\sqrt{f_{c', \text{ nom}}}$

** $0.025\sqrt{f_{c', \text{ nom}}} < f_t \leq \sqrt{f_{c', \text{ nom}}}$
Allowable Stresses: ACI 318-19

Stress at Extreme Fiber in Tension, $f_t$:

- **Class U**: $f_t \leq 7.5 \sqrt{f'_c}$ ($f_t \leq 0.625 \sqrt{f'_c}$ in MPa)
  - One-way: $f_t \leq 7.5 \sqrt{f'_c}$ ($0.625 \sqrt{f'_c}$ in MPa)
  - Two-way slabs: $f_t \leq 6 \sqrt{f'_c}$ ($0.5 \sqrt{f'_c}$ in MPa)
  - Uncracked: Gross cross section properties

- **Class T**: $7.5 \sqrt{f'_c} < f_t \leq 12 \sqrt{f'_c}$ ($0.625 \sqrt{f'_c} < f_t \leq 0.5 \sqrt{f'_c}$ in MPa)
  - Beams and one-way slabs only
  - Transition: Gross cross section properties

- **Class C**: $f_t > 12 \sqrt{f'_c}$ ($f_t > 0.5 \sqrt{f'_c}$ in MPa)
  - Cracked: Cracked section properties

STEP 6 – ANALYSIS

- Calculate post-tensioning force, $P$, as maximum of:
  - $P$ due to balanced load
  - $P$ per allowable average compression
  - Calculate member moments due to gravity loads
  - Compute moments due to PT equivalent loads and calculate secondary moments ($M_2 = M_{bal} - P_e$)
  - Modify tendon drape or force $P$ as required to achieve the targeted balanced load
**STEP 7 – DESIGN**

- Check service load stresses due to $M_{unbal} + P$
- Calculate min. amount of non-prestressed reinforcement
- Calculate temperature and shrinkage reinforcement
- Check ultimate strength & supplement with non-prestressed reinforcement, if required
- Check punching shear and deflection limitations

**STEP 8 – FINAL CHECKS**

- Finalize tendon and reinforcement layout
- Check allowable stresses at:
  - Transfer
  - Service load
  - Extreme top and bottom fibers using the final PT forces (or number of tendons selected)
Serviceability Requirements

- Just after Transfer
  (a) Extreme fiber stress in compression – 0.6 $f'_{ci}$
  (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 – $6\sqrt{f'_{ci}}$

- At Service Loads
  (a) Extreme fiber stress in compression due to prestress plus sustained load – 0.45 $f'_c$
  (b) Extreme fiber stress in compression due to prestress plus total load – 0.6 $f'_c$

PRELIMINARY DESIGN TABLES

PTI DC20.9-11: Guide for Design of Post-Tensioned Buildings

Includes:
- Chapter 2: PT floor systems
- Chapter 3: One-way systems
- Chapter 4: Two-way systems
- Chapter 5: Vertical elements (RTS) and lateral load consideration
- Chapter 6: Preliminary design tables
- Chapter 7: Design and construction details; construction procedures
- Chapter 8: Structural observation and field personnel certification
PTI DC20.9-11 Feature - Design Tables

- Intent of the tables
  - Easy-to-use tools for architects, contractors
  - Starting point for structural design for engineers
  - Provide preliminary estimates for Unbonded PT Slabs subject to gravity loads:
    - Member sizes
    - Post tensioning material quantities (lb/ft²)
    - Nonprestressed reinforcement material quantities (lb/ft²)

Design Basis for Tables

- Gravity loads analysis meeting ACI 318-08 & IBC 2006 with optimal sizes and quantities
  - Post-Tensioning Quantities based on:
    - Min. F/A requirement (non-aggressive environment)
    - Serviceability: stresses and deflection
    - Min. Load Balancing provided = 50% (SW+SDL)
  - Non-Prestressed Reinforcement:
    - Strength
    - Min. Bonded Reinforcement (ACI Code: one-way slab)
Slab Types Covered

### Building Use
- Parking
- Office
- Residential
- Podium

### One-Way
- Narrow Beam + Slab System
  - A. Beams + Joist
  - B. Wide Beam + Slab System

### Two-Way
- Flat Slab with No Drops

Typical Loading, Several Spans and Member Size Combinations
### Table 6.2—Preliminary design table for one-way parking structures (beam and slab system)

#### Design Parameters

Basic design parameters and assumptions:
- **Loading:** DL = Self Weight = 5 psf (SDL)
- LL = 40 psf
- Slab and beam minimum F/A = 125 psi (0.9 MPa)
- Shrinkage and temperature minimum F/A = 100 psi (0.7 MPa) based on ACI 318-08
- Concrete: $f'_{c} = 5000$ psi (34.5 MPa), $f_{y} = 3000$ psi (20.7 MPa)
- Assumed final effective force per $\frac{1}{2}$ strand tendon = 27 kips (120 kN)
- Tendon CGS: Beams 3 in. (76 mm) top and bottom, Slab 1.5 in. (38 mm) top, 1.0 in. (25.4 mm) bottom-interior span, 1.75 in. (44.5 mm) bottom-exterior span
- Cover to nonprestressed reinforcement: Beams 2.0 in. (51 mm) top and bottom, Slab 1.25 in. (31.75 mm) top and 0.75 in. (19 mm) bottom
- Columns size: 24 x 24 in. (610 x 630 mm)

#### Slab Layout

**Parking Example – Extract from Guide**

**Slab Layout**

#### Table 6.2—Preliminary design table for one-way parking structures (beam and slab system)

<table>
<thead>
<tr>
<th>Bay width (X-dir), in.</th>
<th>Slab</th>
<th>Material required</th>
<th>Beams</th>
<th>Material required</th>
<th>Yeast</th>
<th>TOTAL Material Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>58, 58, 58</td>
<td>5</td>
<td>0.218, 0.456</td>
<td>1632</td>
<td>21.8, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>60, 60, 60</td>
<td>5</td>
<td>0.248, 0.426</td>
<td>1634</td>
<td>21.2, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>62, 62, 62</td>
<td>5</td>
<td>0.277, 0.543</td>
<td>1636</td>
<td>20.7, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>58, 58, 58</td>
<td>6</td>
<td>0.277, 0.543</td>
<td>1638</td>
<td>21.2, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>60, 60, 60</td>
<td>6</td>
<td>0.277, 0.543</td>
<td>1640</td>
<td>20.7, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>62, 62, 62</td>
<td>6</td>
<td>0.277, 0.543</td>
<td>1642</td>
<td>20.7, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>58, 58, 58</td>
<td>7</td>
<td>0.277, 0.543</td>
<td>1644</td>
<td>21.2, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>60, 60, 60</td>
<td>7</td>
<td>0.358, 0.691</td>
<td>1646</td>
<td>21.2, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>62, 62, 62</td>
<td>7</td>
<td>0.358, 0.691</td>
<td>1648</td>
<td>20.7, 0.290, 0.027</td>
<td>0.29</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Parking Example – Table Quantities

- Lx = 18 ft (bay width)
- Ly = 60 ft (Beam Span)

Gravity Design Only – Optimal Solution

Member sizes
- Slab = 5 in.
- Beams = 16 x 34 in.

Material from Table
- PT = 0.60 lb/ft²
- Rebar = 1.28 lb/ft²

Other Considerations to Be Added

- Aggressive environment
- Seismic or wind consideration
- Geometry changes, special loading
- Non–prestressed reinforcement for detailing
- Punching shear
### Parking Example – Total Quantities

<table>
<thead>
<tr>
<th>Items</th>
<th>Post Tensioning lb/ft²</th>
<th>Non-Prestressed Reinforcement lb/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Loads</td>
<td>0.60</td>
<td>1.28</td>
</tr>
<tr>
<td>Should precompression be increased from 125psi</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Should load balancing be increased from 50%</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Exterior edge loads</td>
<td>0.03 (assumed)</td>
<td>0.1 (assumed)</td>
</tr>
<tr>
<td>Transverse beams</td>
<td>0.04 (assumed)</td>
<td>0.2 (assumed)</td>
</tr>
<tr>
<td>Transfer girders</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lateral load</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td>Bottom mesh</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td>Backup and support steel</td>
<td>-</td>
<td>0.4 (assumed)</td>
</tr>
<tr>
<td>Misc. Steel (trim and openings)</td>
<td>-</td>
<td>0.2 (assumed)</td>
</tr>
<tr>
<td>Pour strips</td>
<td>-</td>
<td>0.3 (assumed)</td>
</tr>
<tr>
<td>Restraint</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td>Punching shear</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.67</strong></td>
<td><strong>2.48</strong></td>
</tr>
</tbody>
</table>

**SHORTENING RESTRAINT**

**Reasons & Mitigation**

- Building shape
- Restraining elements
- Detailing
What is the PT contribution?
What causes the largest part of shortening?

<table>
<thead>
<tr>
<th>Category</th>
<th>% Of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>7 %</td>
</tr>
<tr>
<td>Creep</td>
<td>9 %</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>56%</td>
</tr>
<tr>
<td>Temperature</td>
<td>28%</td>
</tr>
<tr>
<td>Total</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Shortening

PT Manual:

6.2.3.4 Expansion Joint and Closure Strip Spacing
Guidelines

The following general limitations on the lengths between closure strips and expansion joints are recommended, unless other details or methods are specified to mitigate cracking caused by restraint to shortening:

- If the slab length is less than 250 feet, no closure strip or expansion joint is necessary.
- For slab lengths between 250-325 feet, provide one centrally located closure strip.
- If the slab length is between 325 and 400 feet, consider using two closure strips open for at least 60 days.
- For slabs greater than 400 feet an expansion joint is recommended.
### Closure Strip

- CS’s reduce creep and shrinkage effects
- CS’s remain open until creep and shrinkage has taken place
- 3 to 4 ft wide

- Open for how long?
- Also called delay strip

---

### Creep & Shrinkage vs. Time

vs ~ Volume to Surface Ratio
Arrangement of Shear Walls

(a) Favorable Arrangement of Shear Walls

(b) Unfavorable Arrangement of Shear Walls

Movement Joints

(a) Wall-Slab Release Connection Detail (Option #1)

(b) Wall-Slab Release Connection Detail (Option #2)

(c) Connection of Post-Tensioned Slab to Wall with Splice Sleeves

(d) Connection of Post-Tensioned Slab to Reinforced Wall
DESIGN & CONSTRUCTABILITY ISSUES

- Code Requirements Changes
- Common Design Issues
- Construction Issues

FACTS VS. MYTHS

Facts About PT
- PT concrete is not crack free
- PT concrete is not water proof
- You can drill / make openings in PT slab
- If you drill into a tendon, it will not fly out of the building
- It is possible to upgrade / repair a PT structure
- PT structures are durable
Code Provisions

- ACI 318-11
  Chapter 18 – Prestressed Concrete

- ACI 318-14 (Member based)
  Prestressed concrete provisions within all chapters

- ACI 318-19
  Additional changes

3.2—Referenced standards

423.7-14—Specification for Unbonded Single-Strand Tendon Materials

ACI 423.7 requires the use of encapsulated tendon systems for applications subject to this Code.
Encapsulated anchorage

- Prevent water infiltration and corrosion
- Steel casting coated with corrosion protection
- Lockable encapsulation sleeves
- Lockable encapsulation cap

Shrinkage and Temperature Tendons
Shrinkage and Temperature Tendons

Fig. 87.7.6.3.2—Plan view at slab edge showing added shrinkage and temperature reinforcement.

Minimum Nonprestressed Reinforcement

7.6.2.1 For slabs with bonded prestressed reinforcement, total quantity of $A_s$ and $A_p$ shall be adequate to develop a factored load at least 1.2 times the cracking load calculated on the basis of $f'_c$, as given in 19.2.3.

7.6.2.3 For slabs with unbonded tendons, the minimum area of bonded deformed longitudinal reinforcement, $A_{s,min}$, shall be:

$$A_{s,min} \geq 0.004A_e$$  \hspace{1cm} (7.6.2.3)

where $A_e$ is the area of that part of the cross section between the flexural tension face and the centroid of the gross section.
Common Design Issues

Structural modeling

- DO NOT use simplified analysis using coefficients (Direct Design Method)
- Use the Equivalent Frame Method, EFM
  Sec. 8.11 of ACI 318-14, excluding Sec. 8.11.6.5 and 8.11.6.6. No longer in ACI 318-19 but permitted per Sec. 8.2.1
- DO NOT use middle/column strip concept
- Apply total moment to entire bay section when using EFM

Common Design Issues

Incomplete design

Specify all PT requirements:

- Final effective force, or the number of tendons and corresponding final effective force
- Tendon profile
Serviceability Requirements

- ACI 318-19, Sec. 24.5.2.1
- Not checking initial stress conditions

<table>
<thead>
<tr>
<th>Table R24.5.2.1—Serviceability design requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class U</strong></td>
</tr>
<tr>
<td><strong>Assumed behavior</strong></td>
</tr>
<tr>
<td><strong>Section properties for stress calculation at service loads</strong></td>
</tr>
<tr>
<td><strong>Allowable stress at transfer</strong></td>
</tr>
<tr>
<td><strong>Allowable compressive stress based on uncracked section properties</strong></td>
</tr>
<tr>
<td><strong>Toxic stress at service loads 24.5.2.1</strong></td>
</tr>
<tr>
<td><strong>Deflection calculation basis</strong></td>
</tr>
<tr>
<td><strong>Crack control</strong></td>
</tr>
<tr>
<td><strong>Computation of $S_{ct}$ or $f_{ct}$ for crack control</strong></td>
</tr>
<tr>
<td><strong>Side skin reinforcement</strong></td>
</tr>
</tbody>
</table>

* ($\leq 0.025 f'_c$, metric)  ** ($0.025 f'_c < f_e \leq 0.05 f'_c$, metric)

Common Design Issues

Too much prestressing – using sections that are too small for the amount of force being applied

**24.5.4.1** For Class U and T members, the calculated extreme concrete fiber stress in compression at service loads, after allowance for all prestress losses, shall not exceed the limits in Table 24.5.4.1.

<table>
<thead>
<tr>
<th>Table 24.5.4.1—Concrete compressive stress limits at service loads</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load condition</strong></td>
</tr>
<tr>
<td>Prestress plus sustained load</td>
</tr>
<tr>
<td>Prestress plus total load</td>
</tr>
</tbody>
</table>
Too Much PT?

Not coordinating space at beam/column joints for vertical column bars and PT
Common Design Issues

Not coordinating space at slab/column joints for congestion of rebar and PT

Deviations Around Openings
Common Design Issues

Backup bars and bursting reinforcement, ACI 318-19, Sec. 25.9.4.4.6

Backup Bars and Bursting Steel
Backup Bars and Bursting Steel

ANCHORAGE ZONE REINFORCEMENT
Common Design Issues

Requiring 2 integrity tendons through the column in a one-way slab (when supported on beams) – This applies to 2-way slabs only

8.7.5.6 Structural integrity

8.7.5.6.1 Except as permitted in 8.7.5.6.3, at least two tendons with 1/2 in. diameter or larger strand shall be placed in each direction at columns in accordance with (a) or (b):

(a) Tendons shall pass through the region bounded by the longitudinal reinforcement of the column.
(b) Tendons shall be anchored within the region bounded by the longitudinal reinforcement of the column, and the anchorage shall be located beyond the column centroid and away from the anchored span.

8.7.5.6.3 Slabs with tendons not satisfying 8.7.5.6.1 shall be permitted if bonded bottom deformed reinforcement is provided in each direction in accordance with 8.7.5.6.3.1 through 8.7.5.6.3.3.

8.7.5.6.3.1 Minimum bottom deformed reinforcement $A_t$ in each direction shall be the greater of (a) and (b):

(a) $A_t = \frac{4.5 \sqrt{d h_0}}{f_y}$ (8.7.5.6.3.1a)

(b) $A_t = \frac{300 h_0 d}{f_y}$ (8.7.5.6.3.1b)

where $h_0$ is the width of the column face through which the reinforcement passes.

8.7.5.6.3.2 Bottom deformed reinforcement calculated in 8.7.5.6.3.1 shall pass within the region bounded by the longitudinal reinforcement of the column and shall be anchored at exterior supports.

8.7.5.6.3.3 Bottom deformed reinforcement shall be anchored to develop $A_t$ beyond the column or shear cup face.

Common Design Issues

Not coordinating embed plates for curtain wall systems with the PT anchorage locations
Common Design Issues

Specifying the same force and high/low points in spans of significantly different lengths (overbalancing in the short span):

End bays may require more PT for the same span length
- Reduced tendon drape
- Restrained vs. unrestrained condition
- Heavy exterior skin loads that must be supported by the slab
Common Design Issues

Add tendon anchorage area reinforcement

25.9.4.3 For anchorage devices located away from the end of the member, bonded reinforcement shall be provided to transfer at least $0.35P_{Pa}$ into the concrete section behind the anchor. Such reinforcement shall be placed symmetrically around the anchorage device and shall be fully developed both behind and ahead of the anchorage device.

$$P_{Pa} = \text{factored prestressing force at anchorage device, lb}$$
Displaced Tendons - Inspection

Distributed Tendons at Column

Section through distributed / uniform tendons at column
Column Extension into Slab

Penetrations Near Anchorages
Penetrations in Anchor Zone

Conduit Too Close to Anchors
Bad Duct Layout

Bad Conduit Layout
Conduit Layout

“Eccoduct” Layout
Congestion Near Supports

Elongation Requirements per ACI 318-19, Sec. 26.10.2

(e) Prestressing force and friction losses shall be verified by (1) and (2).
   (1) Measured elongation of prestressed reinforcement compared with elongation calculated using the modulus of elasticity determined from tests or as reported by the manufacturer.
   (2) Jacking force measured using calibrated equipment such as a hydraulic pressure gauge, load cell, or dynamometer.

(f) The cause of any difference in force determination between (1) and (2) of 26.10.2(e) that exceeds 5 percent for pretensioned construction or 7 percent for post-tensioned construction shall be ascertained and corrected, unless approved by the licensed design professional.
Elongation Requirements per ACI 318-14, Sec. 26.10.2

**Elongation Requirements per ACI 318-14, Sec. 26.10.2**

**In practical terms**

1. Use calibrated stressing equipment to stress tendons.
2. Double check prestressing force by measuring elongations and comparing them to the calculated elongations.
3. A tolerance of ± 7% is permitted between measured and calculated elongations without further action.
4. Greater elongation difference needs to be analyzed and possible corrective actions taken as directed by LDP.

**Elongation Discrepancy**

**Causes of Improper Elongation**

- Poor marking procedures
- Inaccurate measurements
- Inaccurate gauge reading
- Improper stressing procedure
- Math errors
- Excessive seating loss
- Equipment malfunction
Analyzing Elongation Discrepancy

- Review marking and measuring procedures
- Check strand modulus of elasticity and cross sectional area
- Consider average effect of beam tendons or banded tendons
- Check for consistency
- Consider other field observations reported
- Possible corrective measures if results not acceptable:
  - Equipment (check calibration; use other set to continue stressing)
  - Restress some tendons (after a day or two)
  - Perform a lift-off on a representative tendon

Broken Tendons
- 2% per ACI 318

Short Tendons
- 40 ft (12.2 m) and shorter
- Consider additional elongation tolerance and lower final effective force (PTI Tech Note 16)
- Tendons should not be shorter that about 20 ft (6.1 m)

Typical Tendon Length
- Single ended pulls < ~ 120 feet
- Double ended pulls < ~ 220 feet
**DETAILING & CONSTRUCTION CONSIDERATIONS**

Constructability

- Can the design objective be accomplished?
  - What should the Engineer consider?

- Communication
  - Preconstruction meeting
  - Who does what?

**Contract Documents**

- **Code**
  - Adopted by Jurisdiction
  - Directed to Engineer

- **Structural Drawings**
  - Prepared by Engineer
  - Results from Design

- **Specifications**
  - Prepared by Engineer
  - Directed to Contractor

- **PT Installation Drawings**
  - Based on Contract Documents
  - Reviewed by Engineer
  - For Construction
Specify all PT requirements:

- **Final effective force**, or the number of tendons and corresponding final effective force
- **Tendon profile**
- Stressing sequence (transfer girders)

**How to specify PT?**

Quality of materials and workmanship...

Both critical to the performance of post-tensioning
PTI Certification Programs

1) Plant Certification (Process Certification)

- Unbonded Tendon Plants (Code requirement)
- PTI – ANSI accredited certification provider
- Plants
  - Unannounced inspections by independent agency
  - Certified, Provisionally Certified, Certification Suspended
  - Actions posted on PTI website

2) Field Personnel Certification Workshops

- Level 1&2 Slab-on-Ground Installer & Inspector
- Level 1 Unbonded PT Installation
- Level 1&2 Unbonded PT Installer & Inspector
- Level 1&2 Unbonded PT Repair, Rehabilitation & Strengthening
- Level 1&2 Multistrand & Grouted PT Specialist
- Level 1&2 Multistrand & Grouted PT Inspector
Placement Inspection Requirements

- Verify number of tendons and CGS from PT Installation and Structural drawings
- Verify that minimum number of tendons pass through column in both directions (2-way slabs)
- Look for tendons with extreme bends, horizontal sweeps, or odd configurations
- Check for damage to sheathing and encapsulation components; record the repairs
- Remove/move excessive conduit, penetrations, etc., especially by the anchors and columns
- Conduit in the slab and penetrations too close to the anchorages

Tendon Finishing

Filling of Stressing Pockets

- Protruding strand tail of proper length to accommodate encapsulation cap; see PT system
- Surface preparation: free from PT coating, grease, form release agent, dirt, loose concrete, etc.
- Bonding agent
- High quality premixed cementitious chloride-free low-shrinkage non metallic repair grout
- Proper mixing and application
BURN OFF TENDON ENDS

HYDRAULIC SHEAR

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REPAIR, REHABILITATION, STRENGTHENING

- Corrosion
- Broken Tendons During Construction
- Repair of Existing Structures
- External Tendons
**Rips and Tears in Sheathing**

- PTI’s Specification for Unbonded Single Strand Tendons states that the tape used should:
  - be self-adhesive and moisture proof
  - be non-reactive with sheathing, P-T coating, and prestressing steel
  - have elastic properties
  - have a minimum width of 2 inches
  - have a contrasting color to the tendon sheathing.
Design of Post-Tensioning Building Structures

Small Openings

Layout Opening and Locate Strands
Demolition

Chip Opening

Expose Strands

De-Tension Tendons
Cast New End Anchorages

Install New Anchors
Pour High Strength Mix

Re-Stress Tendons

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Reinforce Openings if Required

External Post-Tensioning (EPT)
EPT of Precast Double Tees

Rehab. of a Precast Beam
THANK YOU!
This Concludes the Educational Content of This Activity

SURVEY
We welcome your feedback on this seminar. Please complete the survey and return to the presenter