10- Step Design of Post-Tensioned Floors

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301 Mission Street
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High Seismic Force Region

Four Seasons Hotel; Florida
High Wind Force Region

Residential/Office Post-Tensioned Building in Dubai
Column supported multistory building
Two-way flat slab construction

Multi-level parking structures
One-way beam and slab design

Example of a Floor System using the Unbonded Post-tensioning System

Post-Tensioning Systems
Grouted System

An example of a grouted system hardware with flat duct
Example of a Floor System Reinforced with Grouted Post-Tensioning System

Preliminary Considerations
Design of Post-Tensioned Floors

- **Dimensions (sizing)**
  - Optimum spans; optimum thickness

- **Structural system**
  - One-way/two-way; slab band

- **Boundary conditions; connections**
  - Service performance; strength condition

- **Design strips**

- **Design sections; design values**

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An optimum design is one in which the reinforcement determined for “service condition” is *used in its entirety* for “strength condition.”

PT amount in service condition is governed mostly by:

- Hypothetical tensile stresses
- Tendon spacing

Spans: between 7 m – 9 m ft

Span/thickness ratios
- 40 for interior
- 35 for exterior with no overhang

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One-way and two-way systems

- Skeletal Systems *share* load
- Slab systems *may not share* load, depending on reinforcement layout

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(a) ONE-WAY BEAM SYSTEM

(b) TWO-WAY BEAM SYSTEM

Skeletal System
Preliminary Considerations
Design of Post-Tensioned Floors

- One-way and two-way systems
  - Skeletal Systems share load
  - Slab systems may not share load depending on reinforcement layout

- Structural system
  - One-way/two-way; slab band

(b) BEAMS ON FOUR COLUMNS

Capacity required for 100% of load in each direction, if reinforcement is placed along AD, and AC

SLAB BAND

Slab band is treated as part of a two-way system. One-way shear design provisions meant for beams do not apply to slab bands
Subdivide the floor along support lines in design strips.

An important aspect of load path selection in a two-way system is that every point of the slab should be assigned to a specific design strip. No portion of the slab should be left unassigned.

Design sections extend over the entire design strip and are considered at critical locations, such as face of support and mid-span.

Actions, such as moments at each design section are reduced to a "single" representative value to be used for design.

559 k-ft is the area (total) of bending moment at face of support.
10- Steps
Design of Post Tensioned Floors

1. Geometry and Structural System
2. Material Properties
3. Loads
4. Design Parameters
5. Actions due to Dead and Live Loads
6. Post-Tensioning
7. Code Check for Serviceability
8. Code Check for Strength
9. Check for Transfer of Prestressing
10. Detailing

Step 1
Geometry and Structural System

- Select design strip and Idealize
  - Extract; straighten the support line; square the boundary
  - Model the slab frame with a row of supports above and below. This represents an upper level of multi-story concrete frame.
    - Assume rotational fixity at the far ends;
    - Assume roller support at the far ends

Step 2
Material Properties

- Concrete
  - Weight: 24 kN/m³
  - 28 day cylinder: 40 MPa
  - Elastic modulus: 29,725 MPa
  - Long-term deflection factor: 2

- Non-Prestressed reinforcement
  - fy: 460 MPa
  - Elastic modulus: 200,000 MPa

- Prestressing
  - Strand diameter: 13 mm
  - Strand area: 99 mm²
  - Ultimate strength: 1,860 MPa
  - Effective stress: 1,200 MPa
  - Elastic modulus: 200,000 MPa
Step 3
Dead and Live Loads

- Selfweight
  - Based on member volume

- Superimposed dead load
  - Min (partitions) 2.00 kN/m²

- Live load
  - Residential 3.00 kN/m²

Step 4
Design Parameters

- Applicable code
  - ACI 318-14
  - IBC 2012
  - Local codes, such as California Building Code (CBC 2011)

- Cover for protection against corrosion

- Cover to rebar
  - Not exposed to weather 20 mm
  - Exposed to weather 50 mm

- Cover to tendon
  - Not exposed to weather 20 mm
  - Exposed to weather 25 mm

Step 4
Design Parameters

- Cover for fire resistivity

Identify “restrained” and “unrestrained panels.”

<table>
<thead>
<tr>
<th>Restrainted or Unrestrained</th>
<th>Aggregate Type</th>
<th>Cover Thickness, mm for Fire Endurance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrestrained</td>
<td>Carbonate</td>
<td>38 51 -</td>
</tr>
<tr>
<td></td>
<td>Siliceous</td>
<td>38 51 -</td>
</tr>
<tr>
<td></td>
<td>Lightweight</td>
<td>38 51 -</td>
</tr>
<tr>
<td>Restrained</td>
<td>Carbonate</td>
<td>- 19 25 32</td>
</tr>
<tr>
<td></td>
<td>Siliceous</td>
<td>- 19 25 32</td>
</tr>
<tr>
<td></td>
<td>Lightweight</td>
<td>- 19 25 32</td>
</tr>
</tbody>
</table>

For 2-hour fire resistivity
- Restrained 20 mm
- Unrestrained 38 mm

Bottom Cover to Tendon for Fire Resistivity

A = bottom cover for restrained condition
B = bottom cover for unrestrained condition
Step 4
Design Parameters

- Select post-tensioning system
  - For corrosive environment use “encapsulated system.”
  - For non-corrosive environment, regular hardware may be used

- Allowable stresses for two-way systems
  - Service condition
    - Total (frequent) load case
      - Tension \(0.5\sqrt{f'_c}\)
      - Compression \(0.6f'_c\)
    - Sustained (quasi permanent) load case
      - Tension \(0.5\sqrt{f'_c}\)
      - Compression \(0.45f'_c\)
  - Initial condition
    - Tension \(0.25\sqrt{f'_c}\)
    - Compression \(0.6f'_c\)

Step 4
Design Parameters

- Allowable deflections (ACI 318 .5)
  - For visual impact use total deflection
    - Span/240
    - Use camber, if necessary
  - Total deflection subsequent to installation of members that are likely to be damaged
    - Span/360
  - Immediate deflection due to live load
    - Span/480
  - Long-term deflection magnifier 2. This brings the total long-term deflection to 3,

Step 5
Actions due to Dead and Live Loads

- Analyze the design strip as a single level frame structure with one row of supports above and below, using
  - In-house simple frame program (Simple Frame Method; SFM); or
  - in-house Equivalent Frame Program (EFM);
  - Specialty commercial software

- All the three options yield safe designs. But, each will give a different amount of reinforcement.
- The EFM is suggested by ACI-318. To some extent, it accounts for biaxial action of the prototype structure in the frame model.
- 3D FEM software can improve optimization
**Step 5**

**Actions due to Dead and Live Loads**

- Analyze the design strip as a single level frame structure with one row of supports above and below.

![Moments due to DL (k-ft)](chart1)

![Moments due to LL (k-ft)](chart2)

**Step 6**

**Post-Tensioning**

- Selection of design parameters
- Selection of PT force and profile
- Effective force vs tendon selection option
- Calculation of balanced loads; adjustments for percentage of load balanced
- Calculation of actions due to balanced loads

- Two entry value selections must be made to initiate the computations. Select precompression and % of DL to balance

- Select average precompression 1 MPa
- Target to balance 60% of DL

- Assume simple parabola mapped within the bounds of top and bottom covers

![Force diagram of simple parabola](chart3)
**Step 6 Post-Tensioning**

- Assume simple parabola for hand calculation

![Tendon profiles in prototype](image1)

![Tendon profiles for hand calculation](image2)

**Tendon Profiles in Prototype and Hand Calculation**

**STEP 6 Post-Tensioning**

- Calculation of balanced loads; adjustment for % of DL balanced

![Diagram](image3)

**Calculation of balanced loads; adjustment of % of DL balanced**

![Diagram](image4)

**Calculation of balanced loads**
- Lateral forced from continuous tendons
- Lateral force from terminated tendons
- Moments from change in centroid of member

**Example of force from continuous tendon**

\[ P = 500 \text{ k} \]
\[ a = 93 \text{ mm}; \ b = 186 \text{ mm}; L = 9.0 \text{ m}; \ c = \{\frac{93/186}{0.5}\} * 9.00 = 3.73 \text{ m} \]
\[ w_b = 2 \frac{P*a}{c^2} = (2*193*3/1000)/3.73^2 = 1.59 \text{ kN/m per tendon} \]
**STEP 6**

**Post-Tensioning**

- Calculation of balanced loads
  - Lateral force from continuous tendons
  - Lateral force from terminated tendons
  - Moments from change in centroid of member

- Example of force from terminated tendon

![Diagram of a tendon system with forces](image1.png)

\[c = 0.2L; \quad W_b = \frac{2P}{a} \left(\frac{c}{2}\right); \quad R = \frac{2Pa}{c}\]

\[P=\text{tendon force}\]

\[L = 10 \text{ m}; \quad a = 93 \text{ mm}; \quad P = 119 \text{ kN/tendon}\]

\[c = 0.20 \times 10 = 2.00 \text{ m}\]

\[W_b = \frac{(2 \times 119 \times 93)}{1000} / 2 = 5.53 \text{ kN/tendon}\]

Concentrated force at dead end:

\[= \frac{2 \times 119 \times 93}{2000} = 11.06 \text{ kN/tendon}\]

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**STEP 6**

**Post-Tensioning**

- Calculation of actions due to balanced loads
  - Check balanced loads for static equilibrium
  - Determine moments/shears from balanced loads applied to the frame model that was used for dead and live loads
  - Note down reactions from balanced loads

**Example of Balanced Load Assembly**

![Diagram of balanced load assembly](image2.png)

**Comments:**

Moments will be used for serviceability check. Reactions will be used for strength check.
**ACI 318-14 requirements for serviceability**
- Load combinations
- Stress check
- Minimum reinforcement
- Deflection check.

**Load combination**
- Total load condition: \(1.00DL + 1.00LL + 1.00PT\)
- Sustained load condition: \(1.00DL + 0.30LL + 1.00PT\)

**Stress check**
Using engineering judgment, select the locations that are likely to be critical. Typically, these are at the face of support and for hand calculation at mid-span.

At each section selected for check, use the design actions applicable to the entire design section and apply those to the entire cross-section of the design section to arrive at the hypothetical stresses used in code check.

\[
\sigma = \frac{(M_D + M_L + M_{PT})}{S} + \frac{P}{A}
\]

- **In span**
  \(S = I/Y_c\) ;  \(I = \) second moment of area;  \(Y_c = \) distance to farthest tension fiber

**ACI 318-14 Minimum Reinforcement**
- Rebar over support is a function of geometry of the design strip and the strip in the orthogonal direction.
- Rebar in span is a function of the magnitude of the hypothetical tensile stress.

In span, provide rebar if the hypothetical tensile stress exceeds \(0.16\sqrt{f'_c}\).

The amount of reinforcement \(A_s\) is given by:

\[
A_s = \frac{N}{(0.5f_y)}
\]

where \(N\) is the tensile force in tension zone.

\(h =\) member thickness; \(b =\) design section width.
STEP 7
Deflection Check

- Read deflections from the frame analysis of the design strip for dead, live and PT; \((\Delta_{DL}, \Delta_{LL}, \text{ and } \Delta_{PT})\).
- Make the following load combinations and check against the allowable values for each case
  
  - **Total Deflection**
    \[(1 + 2)(\Delta_{DL} + \Delta_{PT} + 0.3 \Delta_{LL}) + 0.7 \Delta_{LL} < \text{span/240}\]
    This is on the premise of sustained load being 0.3 time the design live load. It is for visual effects; Provide camber to reduce value, where needed and practical
  
  - **Immediate deflection** from live load
    \[\Delta_{\text{immediate}} = 1.00\Delta_{L} < \text{span/480}\]
    This check is applicable, where non-structural members are likely to be damaged. Otherwise, span/240 applies
  
  - **Presence of members likely to be damaged** from sustained deflection
    \[(1+ 2)(0.3 \Delta_{LL}) + 0.7 \Delta_{LL} < \text{span/360}\]

STEP 8
Strength Check

- Steps in strength check
  
  - Load combinations
  - Determination of hyperstatic actions
  - Calculation of design moments \((\mu)\)
  - Calculate capacity/rebar for design moment \(\mu\)
  - Check for punching shear
  - Check/detail for unbalanced moment at support

- **Load combinations**
  
  \[U_1 = 1.2DL + 1.6LL + 1.0HYP\]
  \[U_2 = 1.4DL + 1.0HYP\]
  where, \(HYP\) is moment due to hyperstatic actions from prestressing

- **Determination of Hyperstatic actions**
  
  - Direct Method – based on reactions from balanced loads
  - Indirect Method – Using primary and post-tensioning moments

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**STEP 8 Strength Check**

Determination of Hyperstatic actions

- Direct Method – based on reactions from balanced loads

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**A comment on capacity versus demand**

- Post-tensioned members possess both a positive and negative moment capacity along the member length
- Rebar needs to be added, where capacity falls short of demand
- First, find the capacity and compare it with demand

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**Post-Tensioning Actions on Design Strip**

- **Reaction due to balanced loading** (kN; kNm)
  
  \[26.59, -17.73, 4.87, 26.51, 92.73\]

- **Hyperstatic moments** (kNm)
  
  \[163.30, 58.88, 96.24, 133.00, 182.50\]
The figure below shows the forces on a PT member. In calculating the force from PT tendons, use either the ACI 318 or the following simplified procedure, based on parametric study of common building structures can be used for slabs:

- \( f'c \geq 28 \text{ MPa}; \) \( P/A \leq 1.7 \text{ MPa} \)
- \( c/d_t \leq 0.375; d_t \) is distance from compression fiber to farthest tension rebar
- Tendon Length \( \leq 38 \text{ m} \) for single end stressing; if length \( \leq 76 \text{ m} \) double end stressing
- \( f_{ps} \) is conservatively \( 1480 \text{ MPa} \) if span is less than \( 10 \text{ m} \)
- \( f_{ps} \) is conservatively \( 1340 \text{ MPa} \) if span is greater than \( 10 \text{ m} \)

Check for adequate ductility:
- Ductility is deemed adequate, if \( c/d_t \leq 0.345 d_t \) This condition guarantees that steel will yield, before concrete in compression crushes.

Verify adequacy (detail) of the design for transfer of unbalanced moment at supports:
- Unbalanced moment (Mc) is defined as the difference between the design moments on the opposite sides of a column support. This is the moment that is resisted by the support.
- The reinforcement associated with the transfer of unbalanced moment must be placed over a narrow band at the support (next slide)
- In most cases, this provision leads to a “detailing” requirement, as opposed to added rebar, since the reinforcement for slab design is in excess of that needed for transfer of unbalanced moment.

Transfer of unbalanced moment

Place the reinforcement within the narrow band identified as rebar strip.
STEP 9
Check for Transfer of Prestressing

At stressing:
- Tendon has its maximum force;
- Concrete is at its weakest strength; and
- Live load to counteract prestressing is absent

Hence the member is likely to experience stresses more severe than when in service.

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STEP 9
Check for Transfer of Prestressing

At stressing check extreme fiber stresses
- Add rebar when "representative" (hypothetical) tension stresses exceed a threshold
- Do not exceed "representative" hypothetical compressive stresses. Wait until concrete gains adequate strength

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STEP 9
Check for Transfer of Prestressing

- Load combination
  - U = 1.00*Selfweight + 1.15*PT

- Allowable stresses
  - Tension $0.25\sqrt{f'_{ci}}$
  - Compression $0.60f'_{ci}$
  - If tension exceeds, provide rebar in tensile zone to resist $N$
    - $A_s = N / (0.5\ f_y)$
  - If compression exceeds, wait until concrete gains adequate strength
Position of rebar

Thank you for listening.

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