10 - Step Design of Post-Tensioned Floors

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ADAPT

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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

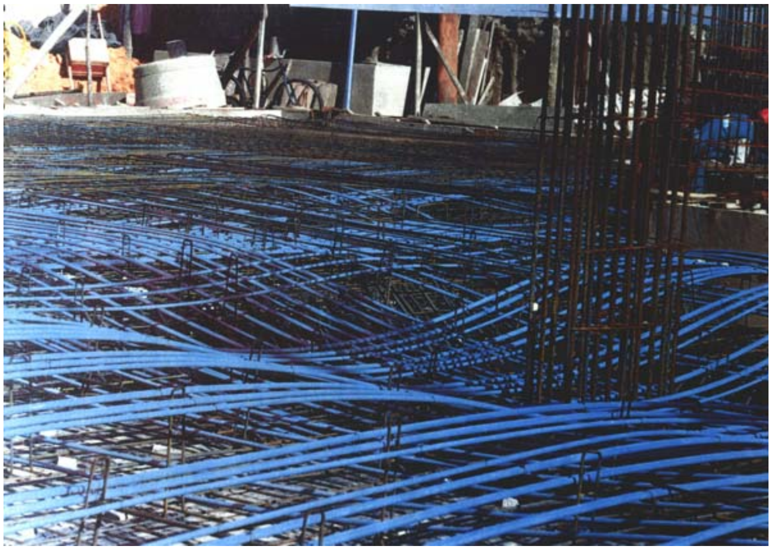
Multi-level parking structures

One-way beam and slab design

Hybrid Construction
Post-tensioned podium slab supporting light framed structure above

Santana Row; San Jose, California

Post-Tensioned ground supported slab (SOG) is the largest application of post-tensioning in USA



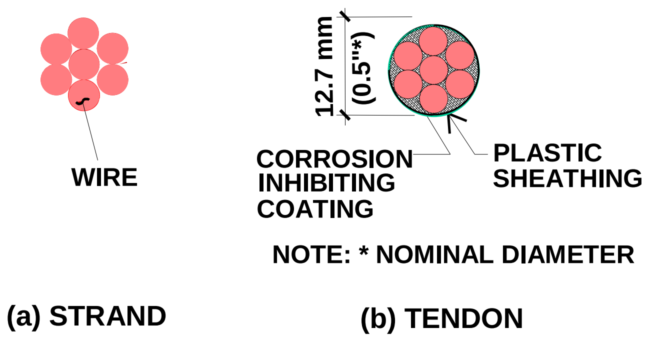
Fortaleza, Brazil

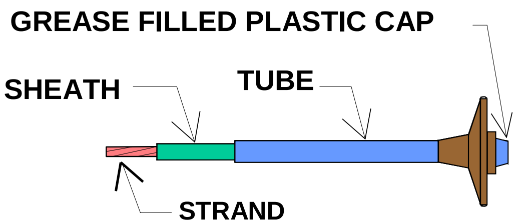
POST-TENSIONED MAT FOUNDATION USING UNBONDED TENDONS

KSA

POST-TENSIONED MAT FOUNDATION USING GROUTED TENDONS

Post-Tensioning Systems
Unbonded System

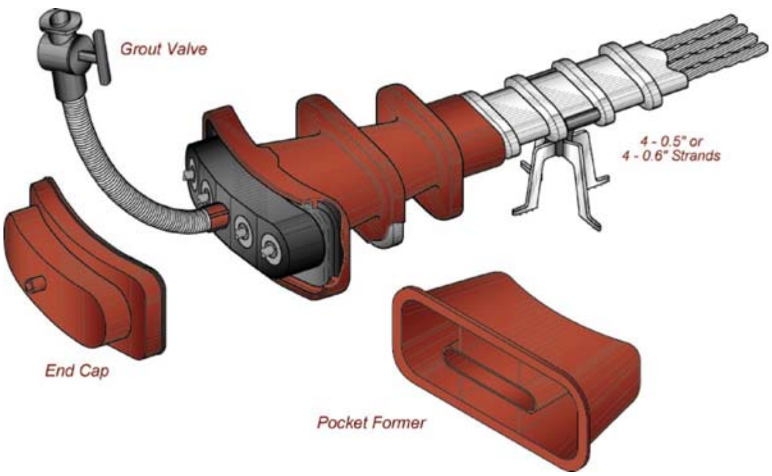




(c) ANCHORAGE ASSEMBLY

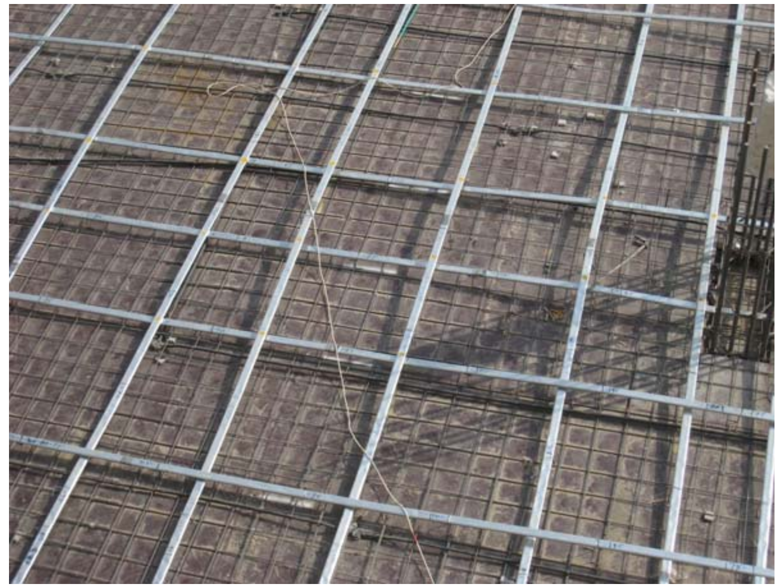
Example of a Floor System using the Unbonded Post-tensioning System

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/beam
- Boundary conditions; connections
  - Service performance; strength condition

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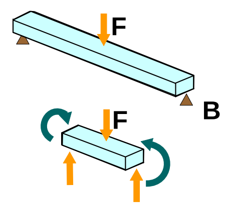
Preliminary Considerations Design of Post-Tensioned Floors

- Dimensions (sizing)
  - Optimum spans; optimum thickness
- An optimum design from standpoint of material usage 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
- Optimum spans: between 25 ft – 30 ft
- Span/thickness ratios
  - 40 for interior
  - 35 for exterior with no overhang

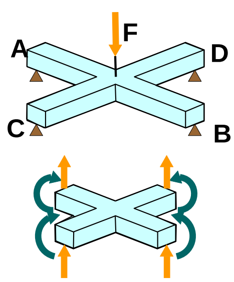
ADAPT

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



(a) ONE-WAY SKELETAL SYSTEM

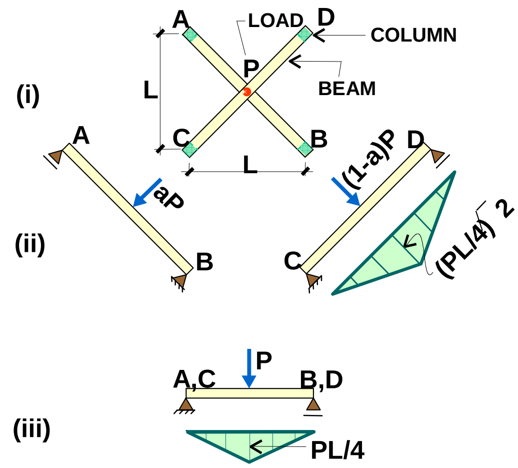


(b) TWO-WAY SKELETAL SYSTEM

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

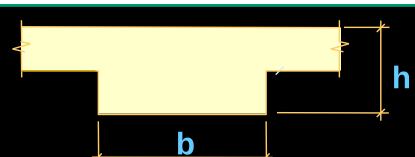


(b) BEAMS ON FOUR COLUMNS

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

Preliminary Considerations
Design of Post-Tensioned Floors

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



$h \leq 2t$ $b \geq 3h$

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

Preliminary Considerations
Design of Post-Tensioned Floors

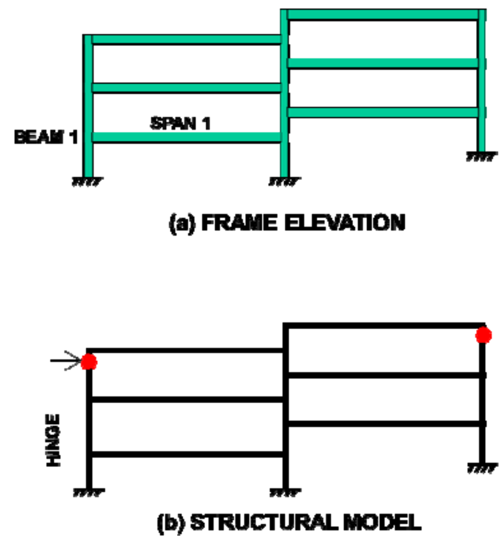
- Selection of boundary conditions; connections
  - Service performance
  - Strength performance

Detailing for service performance, such as the one shown below is to mitigate cracking from shortening of slab

Preliminary Considerations
Design of Post-Tensioned Floors

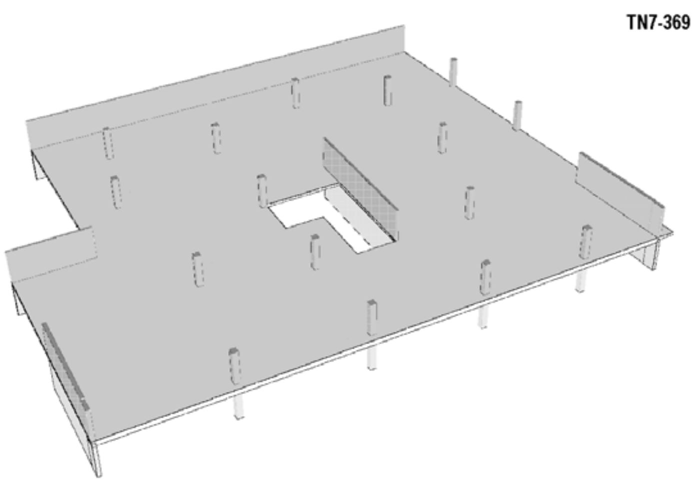
Assumption of releases at connections, or reduced stiffness for selected members is made prior to analysis to achieve a more economical design.

In the following, the assignment of reduced stiffness for the uppermost columns, or hinge assumption at connection is not uncommon



Preliminary Considerations
Design of Post-Tensioned Floors

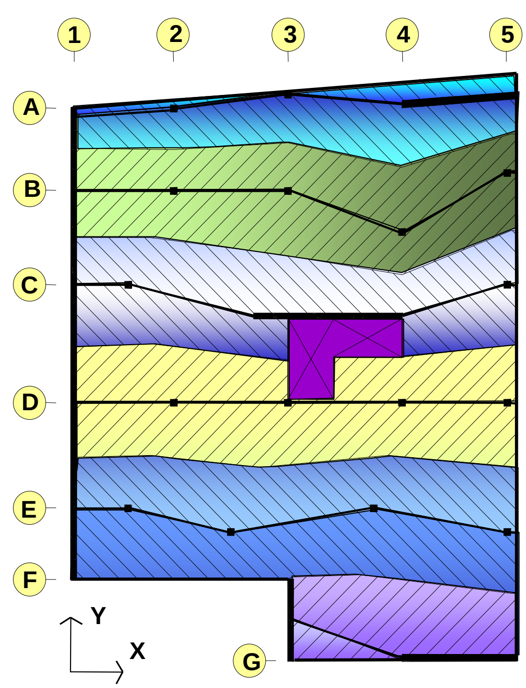
- Selection of load path for two-way systems – Design Strips



Subdivide the structure into design strips in two orthogonal directions
(Nahid slab)

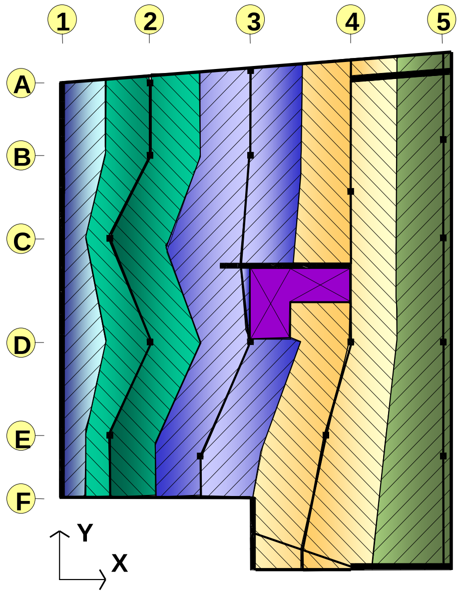
Preliminary Considerations
Design of Post-Tensioned Floors

Subdivide the floor along line of columns into design strips



Preliminary Considerations
Design of Post-Tensioned Floors

Subdivide floor along support lines in design strips in the orthogonal direction

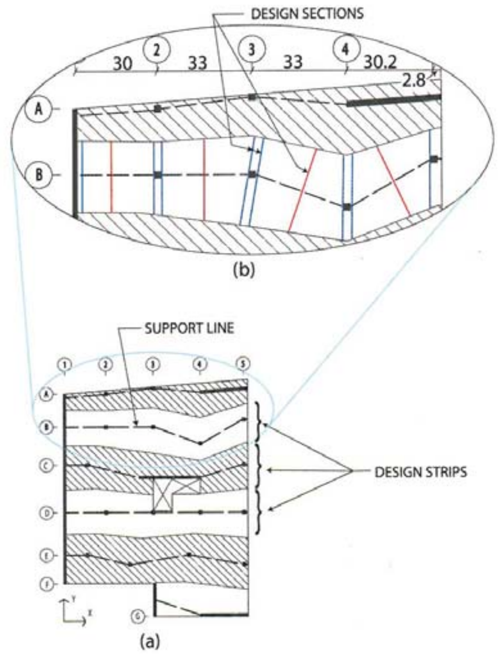


An important aspect subdivision of slab into design strips is that every point of the slab should be covered by a design strip. No portion of the slab should be left unassigned.

Preliminary Considerations
Design of Post-Tensioned Floors

Design sections

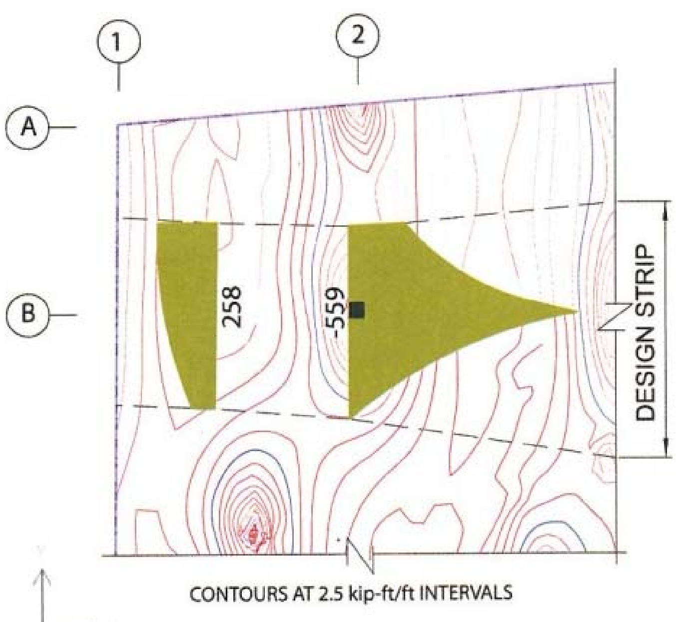
- Design sections extend over the entire design strip and are considered at critical locations, such as face of support and mid-span



Preliminary Considerations
Design of Post-Tensioned Floors

Design values

- 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

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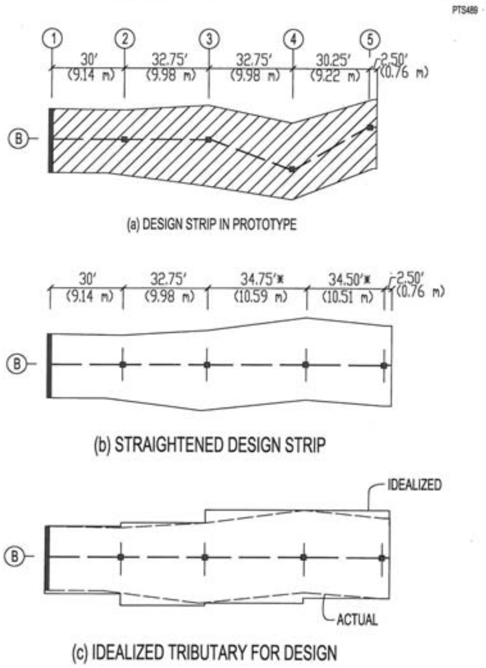
Step 1
Geometry and Structural System

- Select design strip and Idealize
  - Extract; straighten the support line; square the boundary

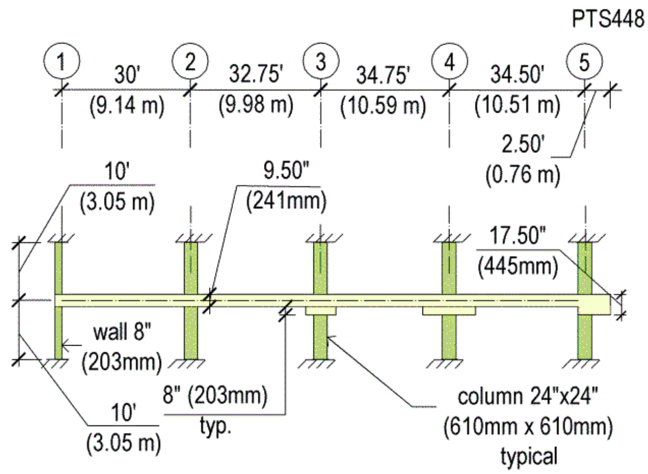


CONSTRUCTION OF DESIGN STRIP IN PLAN

Step 1
Geometry and Structural System

Select design strip and Idealize

- 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



View of idealized slab-frame

Step 2
Material Properties

Concrete

- Weight 150 pcf
- 28 day cylinder 4000 – 6000 psi
- Elastic modulus 3,605 – 5,700 ksi
- Long-term deflection factor 2

- Non-Prestressed reinforcement
  - fy 60 ksi
  - Elastic modulus 29,000 ksi

- Prestressing
  - Strand diameter 0.5 in
  - Strand area 0.153 in2
  - Ultimate strength 270 ksi
  - Effective stress 175 ksi
  - Elastic modulus 28,000 ksi

Step 3
Dead and Live Loads

- Selfweight
  - Based on member volume

- Superimposed dead load
  - Min (partitions) 20 psf

- Live load
  - Residential 40 psf
  - Office 50 psf
  - Shopping mall 75 psf
  - Parking structure 40 psf

- Lateral loads
  - Wind
  - Earthquake

Step 4
Design Parameters

- Applicable code
  - ACI 318-14
  - IBC 2015
  - Local codes, such as California Building Code (CBC 2011)

Cover for protection against corrosion

- Cover to rebar
  - Not exposed to weather 0.75 in
  - Exposed to weather 2.00 in

- Cover to tendon
  - Not exposed to weather 0.75 in.
  - Exposed to weather 1 in.

Step 4
Design Parameters

Cover for fire resistivity

- Identify "restrained" and "unrestrained panels."

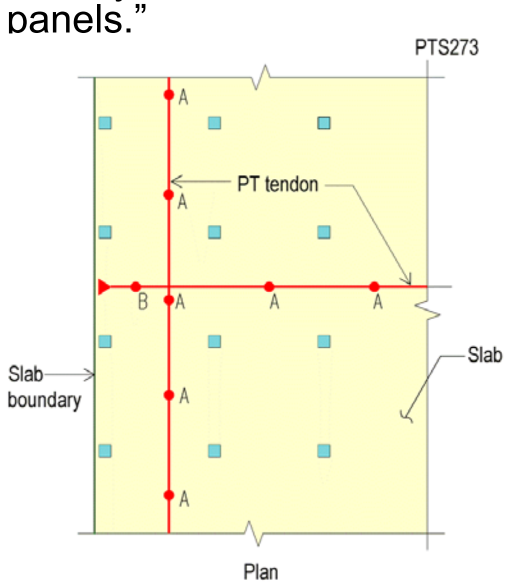
Restrained or Unrestrained	Aggregate Type	Cover Thickness, in. For Fire Endurance of				
		1 hr	1.5 hr	2 hr	3 hr	4 hr
Unrestrained	Carbonate	-	-	1.50	2.00	-
	Siliceous	-	-	1.50	2.00	-
	Lightweight	-	-	1.50	2.00	-
Restrained	Carbonate	-	-	0.75	1.00	1.25
	Siliceous	-	-	0.75	1.00	1.25
	Lightweight	-	-	0.75	1.00	1.25

- For 2-hour fire resistivity
  - Restrained 0.75 in.
  - Unrestrained 1.50 in

Step 4
Design Parameters

Cover for fire resistivity

- Identify "restrained" and "unrestrained panels."



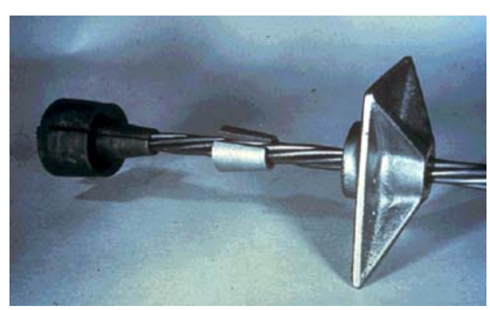
A = bottom cover for restrained condition
B = bottom cover for unrestrained condition

Bottom Cover to Tendon for Fire Resistivity

Step 4
Design Parameters

- Select post-tensioning system
  - For corrosive environment use "encapsulated system."

  - For non-corrosive environment, regular hardware may be used



Step 4
Design Parameters

❑ Allowable stresses for two-way systems

❖ Service condition

➢ Total (frequent) load case

- Tension --------------------------- $6\sqrt{f_c^{'}}$
- Compression --------------------$0.6 f_c^{'}$

➢ Sustained (quasi permanent) load case

- Tension -------------------------- $6\sqrt{f_c^{'}}$
- Compression -----------------$0.45 f_c^{'}$

❖ Initial condition

- Tension ------------------------ $0.6\sqrt{f_c^{'}}$
- Compression -------------- $0.45 f_c^{'}$

Step 4
Design Parameters

❑ Allowable deflections (ACI 318)

❖ 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

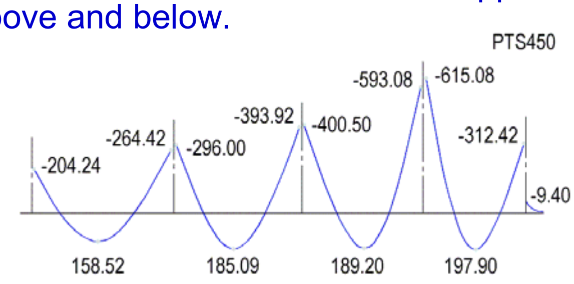
❖ All the three options yield safe designs. But, each will give a different amount of reinforcement.

❖ The EFM is suggested by ACI-318. To some extent, it accounts for biaxial action of the prototype structure.

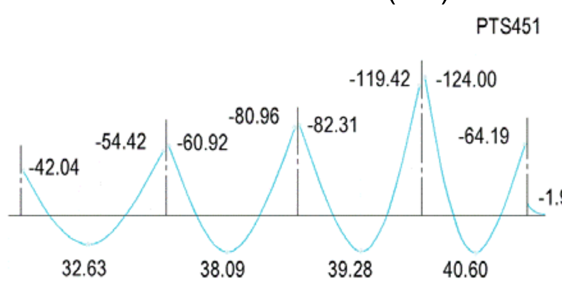
❖ 3D FEM software can improve optimization.

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)



Moments due to LL (k-ft)

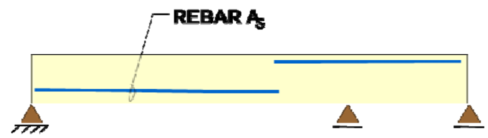
Step 6
Post-Tensioning

Selection of design parameters

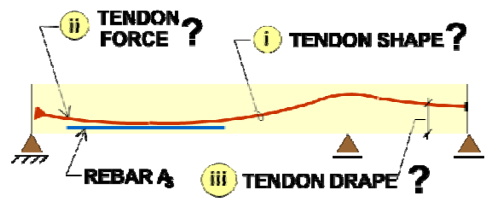
- Selection of PT force and profile
- Effective force vs tendon selection option
  - Force selection option
- Calculation of balanced loads; adjustments for percentage of load balanced
- Calculation of actions due to balanced loads

Step 6
Post-Tensioning

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



(a) NONPRESTRESSED MEMBER



(b) POST-TENSIONED MEMBER

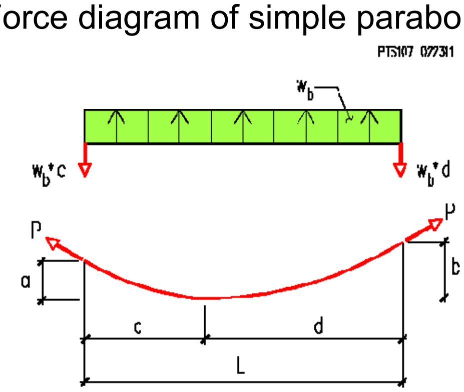
Step 6
Post-Tensioning

Selection of design parameters

- Select average precompression 150 psi
- Target to balance 60% of DL

- Selection of PT force and profile
  - Assume simple parabola mapped within the bounds of top and bottom covers

Force diagram of simple parabola

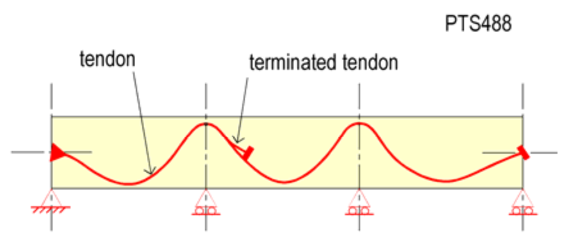


$$c/L = [\sqrt{a/b} \;/\; (1 + \sqrt{a/b})]$$

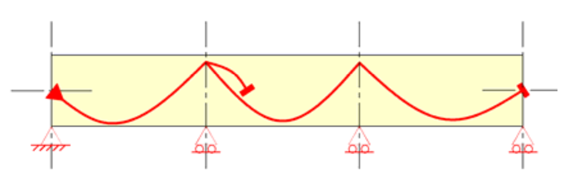
$$w_b = 2P * c/c^2$$

Step 6
Post-Tensioning

- Assume simple parabola for hand calculation



(a) Tendon profiles in prototype



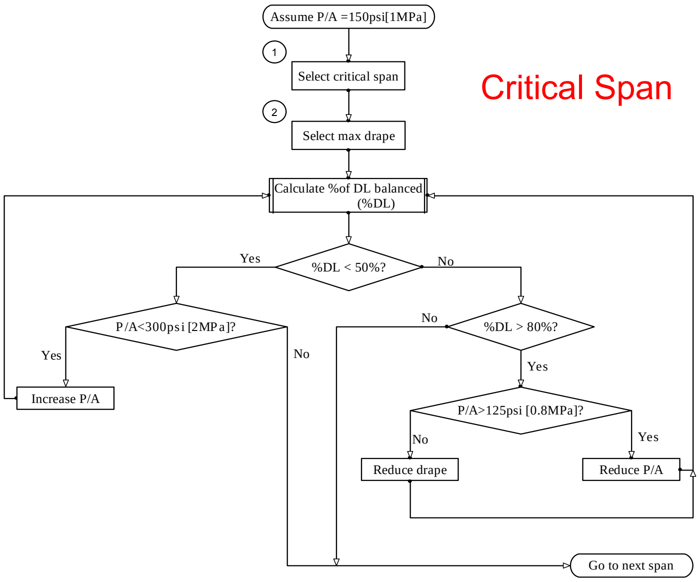
(b) Tendon profiles for hand calculation

Tendon Profiles in Prototype and Hand Calculation

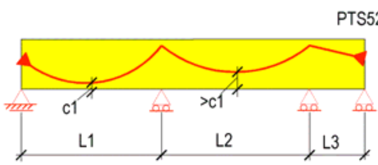
STEP 6
Post-Tensioning

❖ Flow chart for calculation of balanced loads and adjustment for % of DL balanced

F121_ACI_PT_2_way_082012



Critical Span

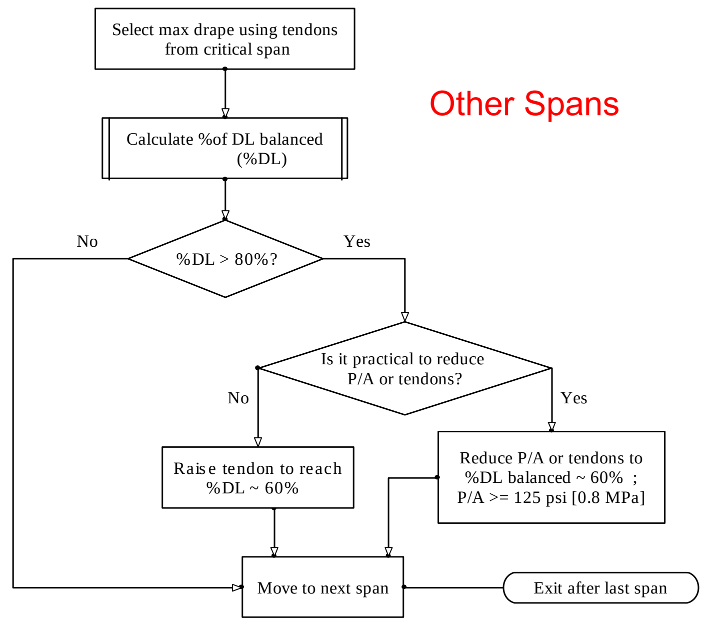


Element with widely different spans

STEP 6
Post-Tensioning

❖ Flow chart for calculation of balanced loads and adjustment for % of DL balanced

F121_ACI_2-way_PT_force_082012



Other Spans

STEP 6
Post-Tensioning

❖ Effective force per strand
  ➢ Unbonded: 0.153x175 = 26.77 k/tendon
  Bonded: 0.153x160 = 24.48 k/tendon

❖ Estimate initial force for each span using the assumed 150 psi precompression

Span 1

Force = (26.77x12x9.5)x150/1000 = 448.88 k

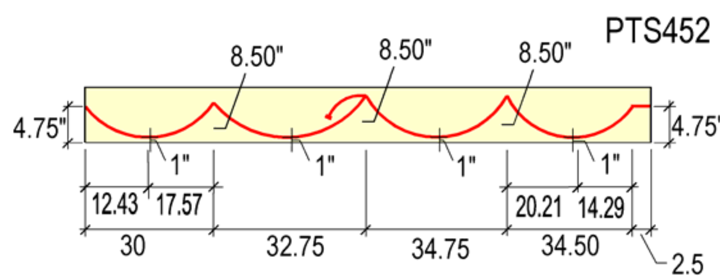
No of tendons = 448.88/26.77 = 16.77 assume 17 strands

Similarly the required strands are:

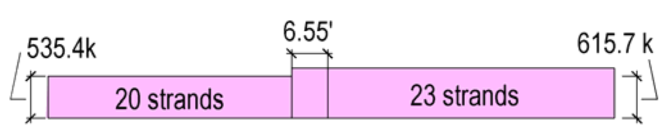
	required		assumed
Span 1	17	------------------	20
Span 2	20	------------------	20
Span 3	23	------------------	23
Span 4	22	------------------	23

STEP 6
Post-Tensioning

❖ Tendon selection



(a) Assumed tendon profile (ft UNO)

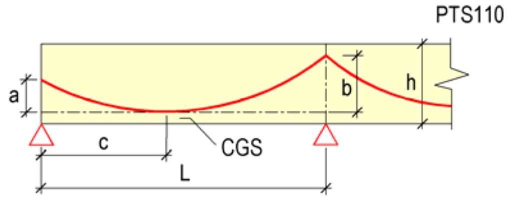


(b) Force diagram

Post Tensioning Profile and Force

STEP 6 Post-Tensioning

- Calculation of balanced loads
- Span 1



a = 3.73 in

b = 7.5 in

L = 30.00 ft

$c = \{[3.75/7.5]^{0.5}/[1 + (3.75/7.5)^{0.5}]\}*30 =$

$= 12.43$ ft

P = 26.77 k/strand

$w_b = 2\ P*a/c^2 = (2*26.77*3.75/12)/12.43^2$

$= 0.108$ klf per tendon

Total uplift for 20 strands = 20*0.108= 2.16 klf

% uplift = (2.16/3.826)x100 = 56% <60%

but considered acceptable

STEP 6 Post-Tensioning

- Calculation of balanced loads
  - Span 2
  - Span 2 has 20 continuous tendons and 3 tendons from span 3 extending to span 2

- Balanced loads of span 2 consist of:
  - Lateral forced from continuous tendons
  - Lateral force from terminated tendons
  - Moments from change in centroid of member

Continuous strands:

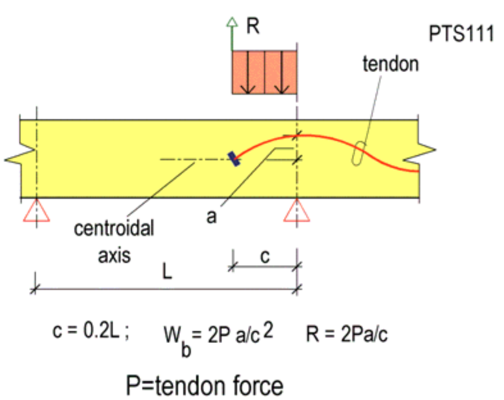
$w_b = 8\ P*a/L^2$

$= (8*26.77*7.5/12)/32.75^2 = 0.125$ klf

% of DL= (20*0.125/4.482)100 = 56 % OK

STEP 6 Post-Tensioning

- Calculation of balanced loads
  - Lateral force from terminated tendons



L = 32.75 ft ; a = 3.75 in; P = 26.77 k/tendon

c = 0.20*32.75 = 6.55 ft

$w_b = (2*3*26.77*3.75/12)/6.55^2 = 1.17$ k/lft ↓

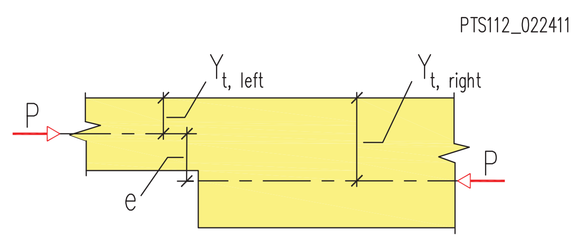
Concentrated force at dead end =

= 2*3*26.77*3.75/12*6.55= 7.66 k ↑

STEP 6 Post-Tensioning

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

- Example of force from shift in member centroidal axis



Moment at face of drop = M

$M = P * \text{shift in centroid} = P * (Y_{t\text{-Left}} - Y_{t\text{-Right}})$

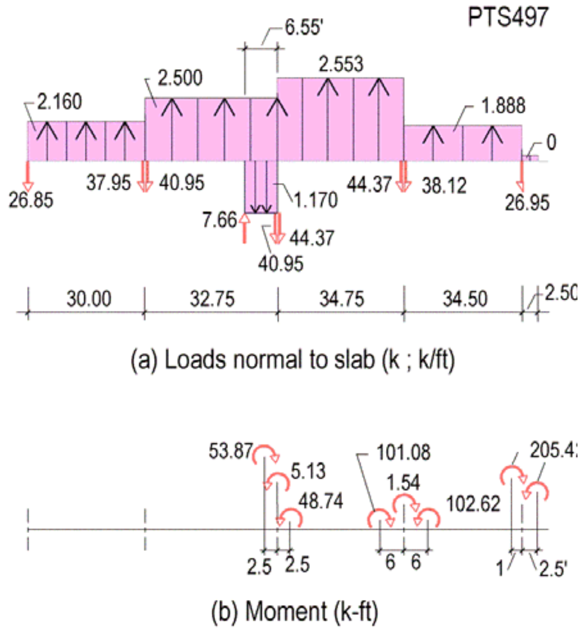
P = 23*26.77= 615.71 k;

$Y_{t\text{-Left}} = 4.75"$; $Y_{t\text{-Right}} = 5.80"$

M = 615.71(4.75"– 5.80")/12 = -53.87 k-ft

STEP 6
Post-Tensioning

- Check balanced loads for static equilibrium
  - Sum of forces must add up to zero
  - Sum of moments must add up to zero
  - Correct errors, if equilibrium is not satisfied

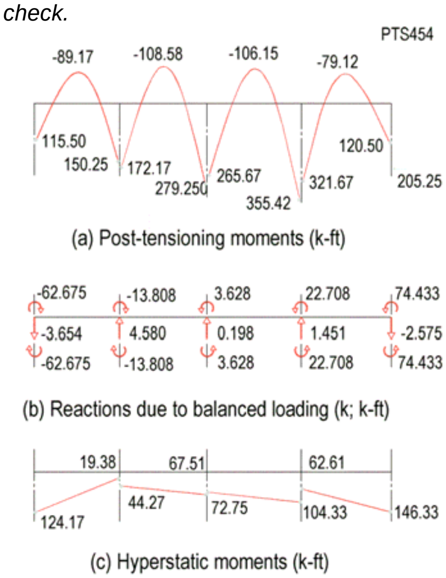


Balanced Loading

STEP 6
Post-Tensioning

- Calculate actions from balanced loads
  - Obtain moments at face-of-supports and mid-spans
  - Note the reactions. The reactions are hyperstatic forces..

Comments:
Moments will be used for serviceability check. Reactions will be used for Strength check.



Post-Tensioning Actions on Design Strip

STEP 7
Code Check for Serviceability

- ACI 318-14 requirements for serviceability
  - Stress check
  - Minimum reinforcement
  - Deflection check.

- Load combinations
  - Total (quasi permanent)
    1.00DL + 1.00LL + 1.00PT
  - Sustained (frequent)
    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 them to the entire cross-section to arrive at code-intended hypothetical stresses used in code check.

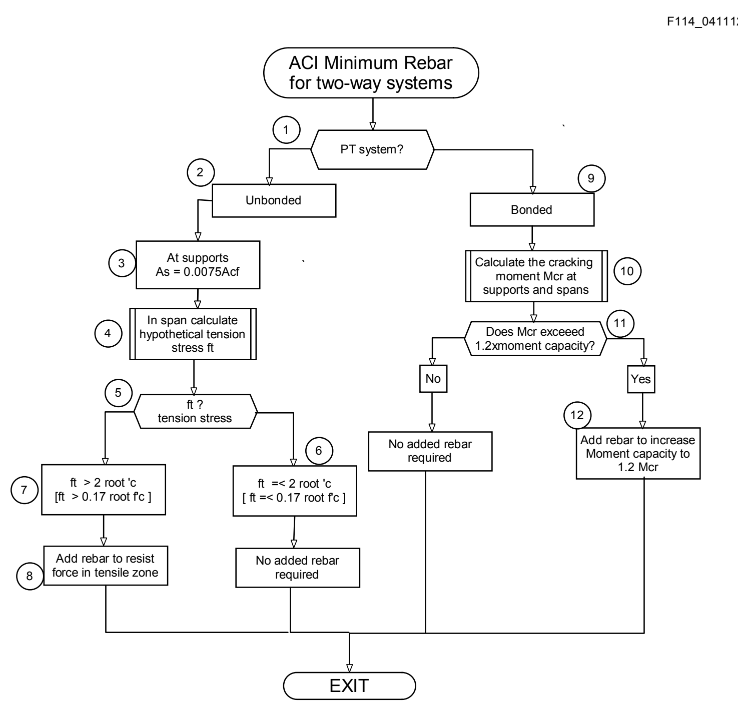
$$\sigma = (M_D + M_L + M_{PT})/S + P/A$$

$S = I/Y_c$; I = second moment of area of ;

Y_c= distance to farthest tension fiber

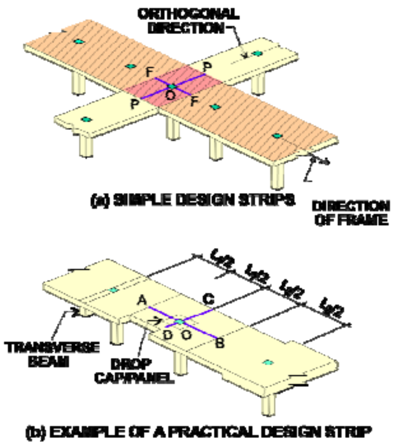
STEP 6
Post-Tensioning

- ACI 318-14 Minimum Reinforcement



STEP 6
Post-Tensioning

- ACI 318-14 Minimum Reinforcement
  - Rebar over support is 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



$As = 0.00075 * A_{cf}$

As = Area of steel required

A_{cf} = Larger of cross-sectional area of the strip in direction of analysis and orthogonal to it.

STEP 6
Post-Tensioning

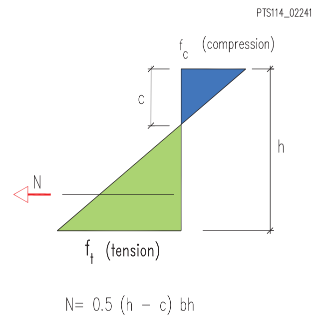
- ACI 318-14 Minimum Reinforcement
  - Rebar over support is function of geometry of the design strip and the strip in the orthogonal direction
  - Rebar in span is a function of the magnitude of the hypothetical tensile stress

In span, provide rebar if the hypothetical tensile stress exceeds $2\sqrt{f'_c}$

The amount of reinforcement A_s is given by:

$A_s = N / (0.5 f_y)$

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; (Δ_{DL} , Δ_{LL} , and Δ_{PT}).
- . Make the following load combinations and check against the allowable values for each case

  - Total Deflection
    $(1 + 2)(\Delta_{DL} + \Delta_{PT} + 0.3 \Delta_{LL}) + 0.7 \Delta_{LL} < span/240$
    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
    $\Delta_{immediate} = 1.00\Delta_L < span/480$
    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
    $(1+ 2)(0.3 \Delta_{LL}) + 0.7 \Delta_{LL} < span/360$

The above can be exceeded, if larger values are acceptable for the specific application

STEP 8
Strength Check

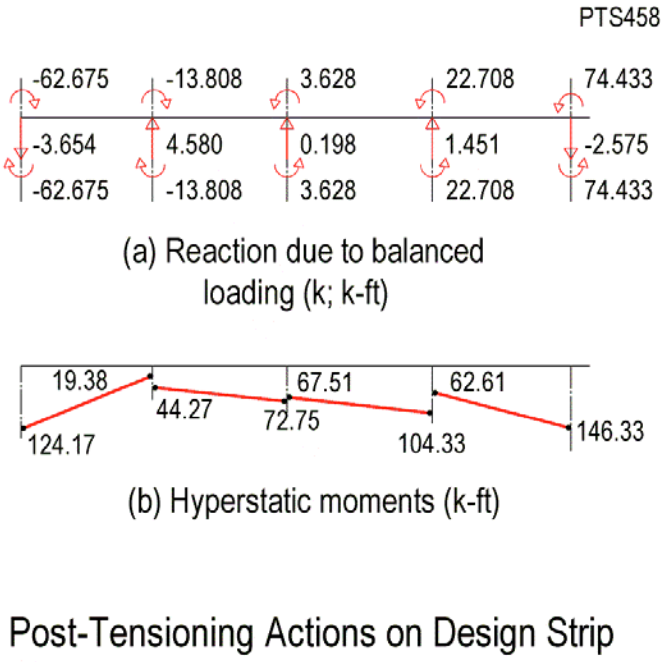
- Steps in strength check
  - Load combinations
  - Determination of hyperstatic actions
  - Calculation of design moments (Mu)
  - Calculate capacity/rebar for design moment Mu
  - Check for punching shear
  - Check/detail for unbalanced moment at support

- Load combinations
  U1 = 1.2DL + 1.6LL + 1.0HYP
  U2 = 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

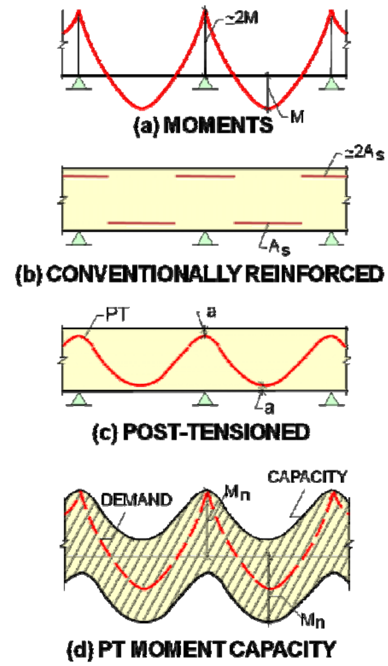
STEP 8
Strength Check

- Determination of Hyperstatic actions
  - Direct Method – based on reactions from balanced loads



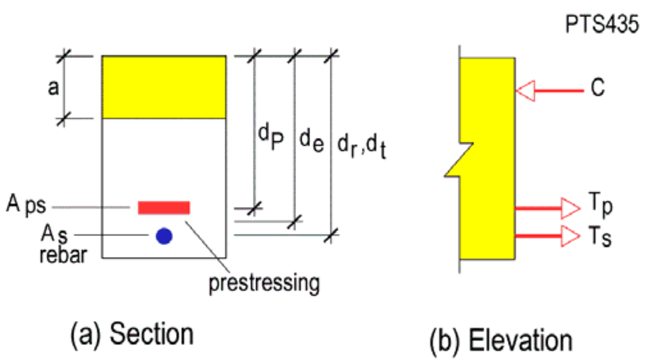
STEP 8
Strength Check

- A comment on capacity versus demand
  - Post-tensioned elements possess both positive and negative moment capacity along the entire element's length
  - Add rebar , where capacity falls short of demand
  - Find capacity and compare it with demand



STEP 8
Strength Check

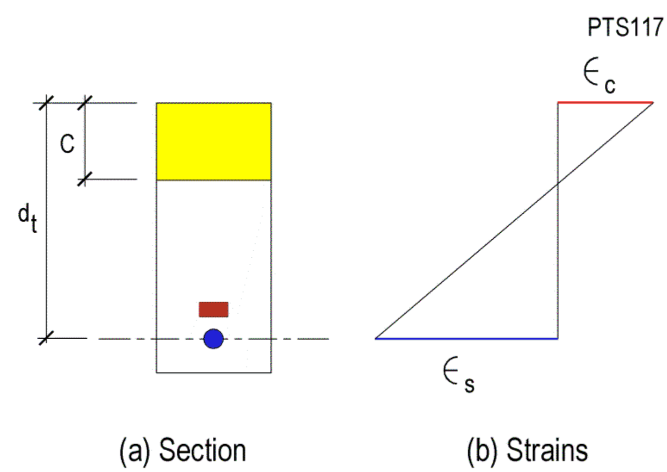
- For capacity calculation use the simplified relationship applicable to common building structures reinforced with unbonded tendons



- $f'_c \geq 4000$ psi ; $P/A \leq 250$ psi
- $c/d_t \leq 0.375$; d_t is distance from compression fiber to farthest tension rebar
- Tendon Length ≤ 125' for single end stressing; if length ≤ 250' double end stressing
- f_{ps} is conservatively 215 ksi if span is less than 35 ft
- f_{ps} is conservatively 195 ksi if span is greater than 35 ft

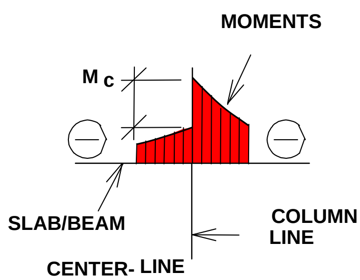
STEP 8
Strength Check

- Check for ductility
  - Ductility is adequate, if c/dt <= 0.345 dt
    This condition guarantees that steel will yield, before concrete in compression crushes.
  - Add compression rebar if c/dt > 0.345 dt



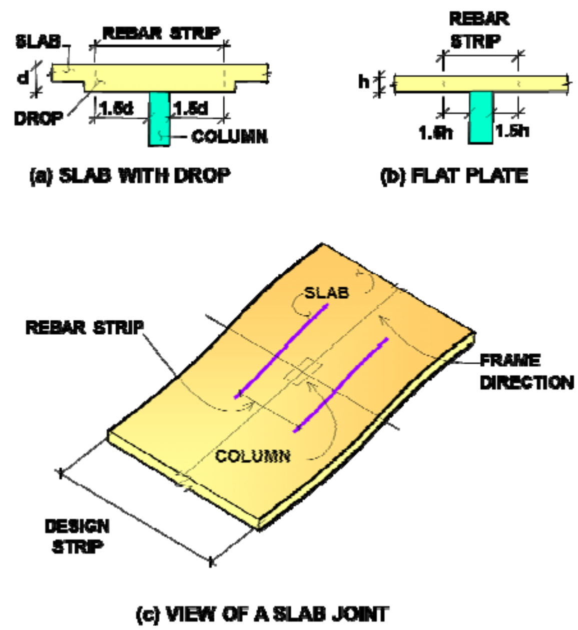
STEP 8
Strength Check

- 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.



STEP 8
Strength Check

- Transfer of unbalanced moment



Place the reinforcement within the narrow band identified as rebar strip

Punching Shear Design

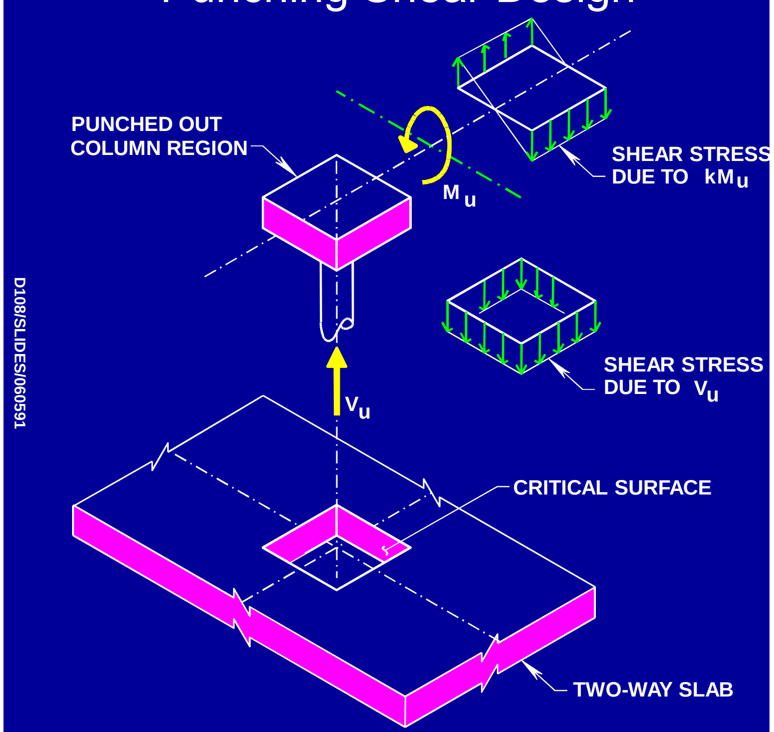


ILLUSTRATION OF CRITICAL SURFACE
FOR THE EVALUATION OF PUNCHING SHEAR STRESSES

Definition based on ACI 318

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

STEP 9
Check for Transfer of Prestressing

- Add rebar where "representative" (hypothetical) tension stresses exceed the allowable threshold
- Do not exceed "representative" hypothetical compressive stresses. Wait until concrete gains adequate strength

STEP 9
Check for Transfer of Prestressing

- Load combination
  - U = 1.00*Selfweight + 1.15*PT
- Allowable stresses
  - Tension $3\sqrt{f'_{ci}}$;
  - Compression $0.60 f'_{ci}$
  - If tension exceeds, add rebar in tensile zone to resist N

    As = N / (0.5 fy)

✓ If compression exceeds, wait until concrete gains adequate strength

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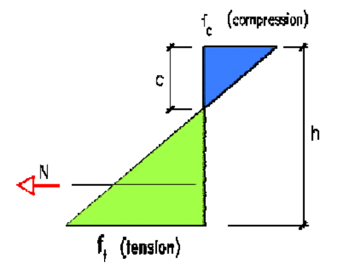
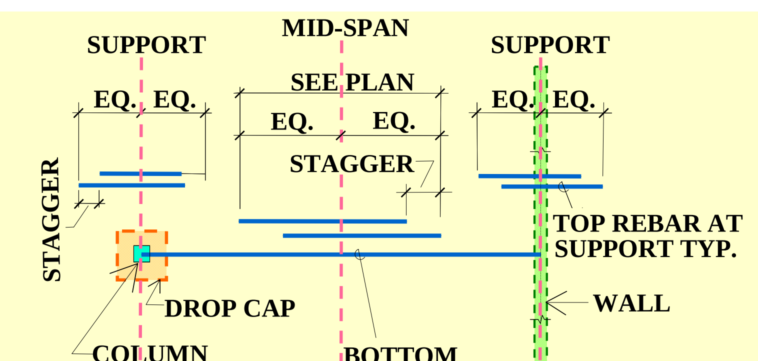
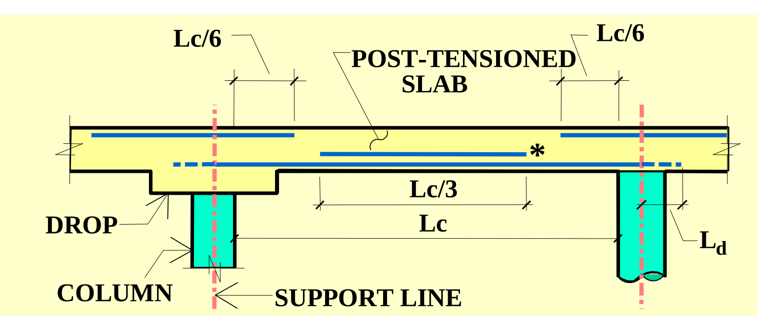


STEP 10
Detailing

- Position of rebar



PLAN



ELEVATION

Thank you for listening

QUESTIONS ?

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