PDHonline Course S127 (2 PDH)

General Overview of Post-Tensioned Concrete Design

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Definitions:

Prestressed Concrete: A condition in which the member is stressed via tensioned tendons prior to application of external loads.

Types of prestressed concrete include:

- Pretensioned - tendons are stressed prior to casting of concrete; strands anchored to external abutments or self-stressing form prior to transfer of prestressed force to hardened concrete. Strands are typically bonded (i.e. force transfer to concrete via mechanical bond between stranded wire and surrounding concrete)

- Post-Tensioned - tendons are stressed after concrete is cast and hardened; strands are anchored against concrete member. Strands are typically unbonded (i.e. anchored only at the ends via anchorage assembly) but can be bonded (i.e. stressed in ducts and grouted in place in addition to end anchorages)

Design Philosophy:

Eccentricity of tensioned cables produces internal moments that act in opposition to moments induced by external loading. Pre-compression of concrete (Force/Area or P/A) also helps to control cracking and also improves other serviceability issues such as deflection.

Typically the required prestressing force (i.e. number, size and profile of tendons) is determined by service stress conditions.

$$f_b = (P/A \pm M_{net}/S) < \text{or} = f_{allowable}$$

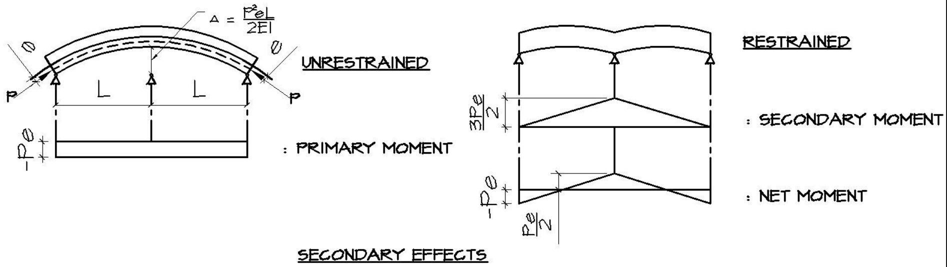
$$\text{Where: } M_{net} = [(M_{DL+LL}) - M_{balancing}]$$

The ultimate flexural and shear capacity of the section are then checked at the required critical points.

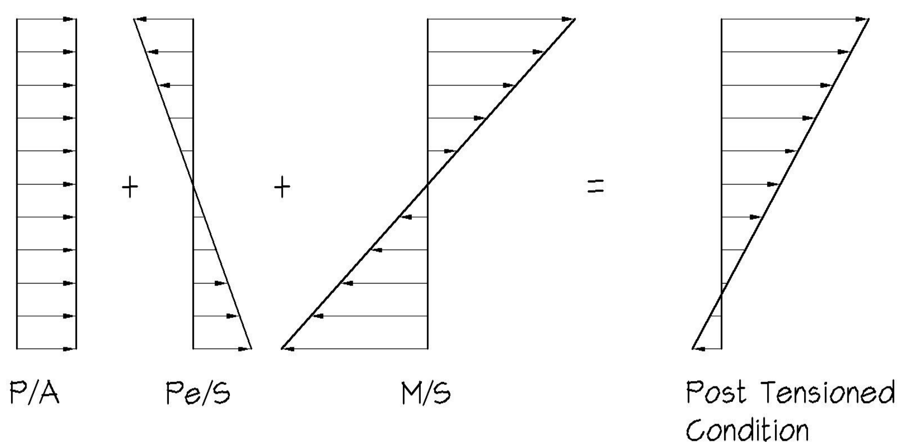
Analysis:

Primary & Secondary Moments due to Post-Tensioning;

In simple span beams the primary post-tensioning (P/T) moments induced by the prestressing force are directly proportional to the eccentricity of the tendons with respect to the neutral axis of the member (i.e. Pe). In continuous or indeterminate post-tensioned structures the moments due to the prestressing force are typically not directly proportional to the tendon eccentricity. This condition occurs because the deformation (i.e. camber) of the member imposed by the P/T force is restrained where it is continuous over other supporting members within the structure. This restraint modifies the reactions and therefore affects the elastic moments and shears resulting from the P/T force. The moments resulting from these restraints are called secondary moments. This term refers to the fact that these moments are induced by the primary Pe and not because they are negligible or necessarily smaller than the primary moment. It is important to note that secondary moments are functions of the reactions and therefore vary linearly between supports. In addition, the total P/T moment is equal to the super-position of the Pe and secondary moments.



In most continuous structures secondary moments have the effect of increasing the magnitude of the positive P/T moment at interior supports and reducing the negative P/T moment between supports. ACI-318 requires that the secondary moments (with a load factor of 1.0) be included in the strength design of a member. Secondary effects are typically not, however, included in the service stress analysis.



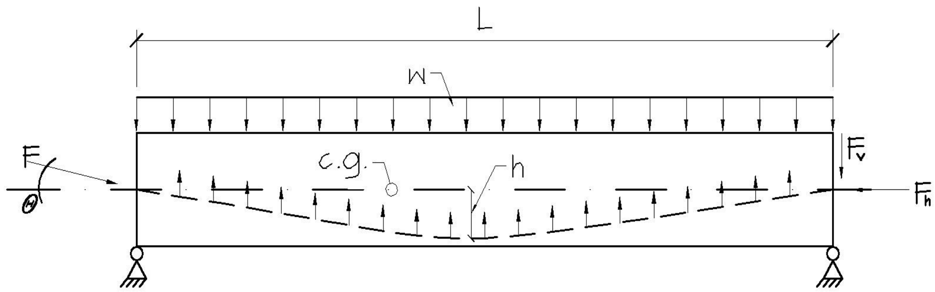
Methods of Analysis include:

1. Area Moment
2. Equivalent Load
3. Load Balancing: Introduced by T.Y. Lin in June 1963. The basic concept of load-balancing is also a representation of the influence of tendons by using equivalent loads. This method is by far the most convenient method and recommended by PTI.

This course only provides information concerning the Load Balancing method of analysis.

Load-Balancing:

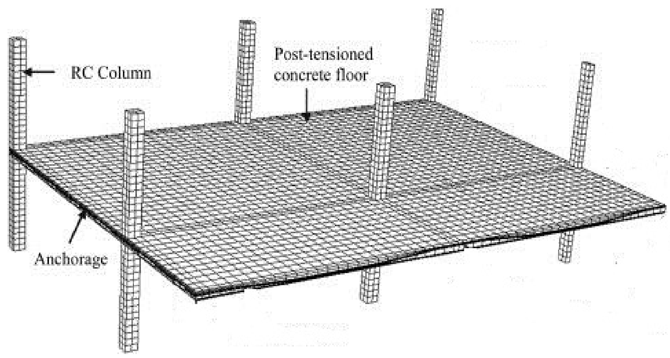
A magnitude of prestressing force is selected to "balance" or counteract some portion of the load. A theoretically perfectly "balanced" structure would result in no deflection and only axial compression forces (P/A) from the tendons. The net moment at any point within a beam is therefore that moment that results from that portion of a load that is not balanced. This concept helps visualize the effects of post-tensioning on any structure and greatly simplifies the calculations. In addition, secondary moments are easily obtained by subtracting the primary Pe from the moments caused by the balancing load at any location along the beam.



FOR PARABOLIC CABLE : $F = F_h = \frac{wL^2}{8h}$

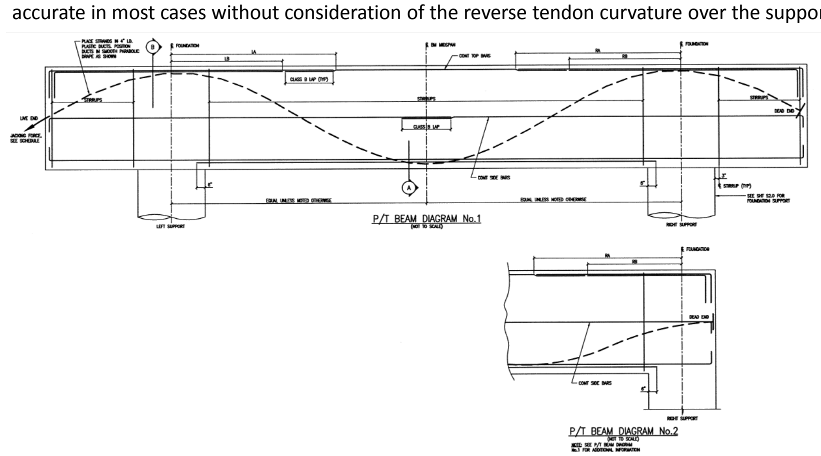
LOAD BALANCING

This initial portion of the analysis is very iterative and “trial and error” in nature. Because of this there are a number of different approaches to establishing a starting point. Some engineers like to think in terms of a percentage of dead or live load as basis for starting the analysis. From my experience, however, particularly with structures having highly variable spans and loading conditions I like to start with a tendon profile based on experience and simply run the numbers (friction, wedge set & other losses and initial service stress analysis). From these results I then make adjustments to the strand drape and jacking sequence as necessary.



Source: Engineering Structures

It is also important to note that the load-balancing method assumes a sharp bend in the tendon geometry over the supports. In reality the tendons are laid over supports with a reverse curvature to help minimize frictional losses during the stressing operation. Tests have shown however that for practical tendon geometries (in particular with flat plate construction) the effects of the actual tendon profile over the supports are only in the order of between 5% and 10% error. As the calculated load-balancing moments only directly effects service stress calculations more so than ultimate strength the load-balancing method is therefore sufficiently accurate in most cases without consideration of the reverse tendon curvature over the supports.



Design:

Preliminary Sizing of Members:

The following table of Span-to-Depth ratios is recommended for the initial preliminary sizing of members:

Construction Type	Continuous Span		Simple Span	
	Roof	Floor	Roof	Floor
One-Way Solid Slabs	50	45	45	40
Two-Way Solid Slabs	45-48	40-45	N/A	N/A
Beams	35	30	30	26
One-Way Joists	42	38	38	35

Tendons:

Typically tendons are located near the bottom fiber at positive moment regions and near the top fiber at negative moment regions with the intent to install the cable with the maximum total drape. Exceptions include the need to anchor at the neutral access of an exterior end support condition which can be particularly limiting at a flat plate structure. In addition, the variability of adjacent spans lengths or loading conditions will also have an impact on the final tendon geometry.

Types of tendons can include:

1. Bonded
2. Unbonded

Arrangements of tendons include:

1. Parabolic Drape
2. Straight Line (typically only used in pretensioned member)
3. Horizontal Sweep

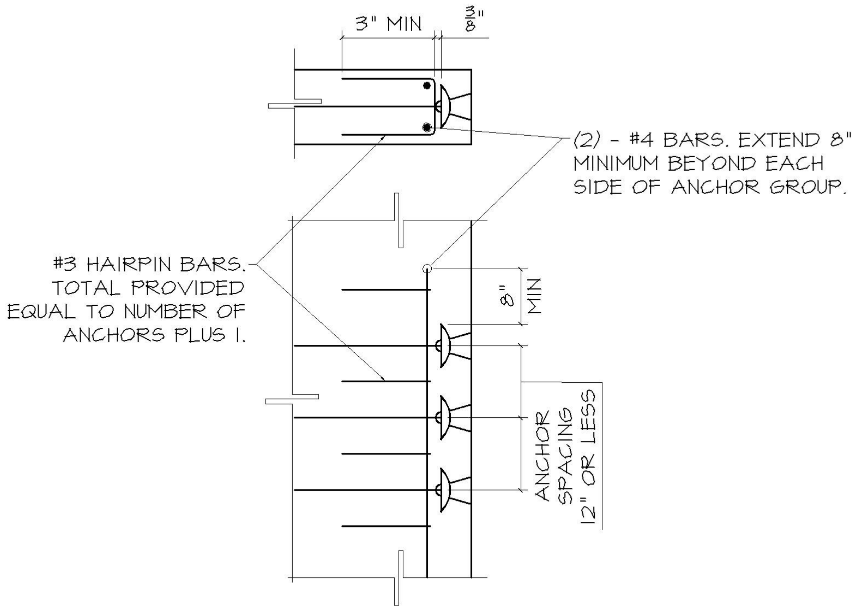
Placement & Details:

A. Tendons at the “high points” that join adjacent draped strand profiles exert downward reactions. The tendons should be laid out so that these reactions occur and can in turn be resisted by columns, walls and/or “upward” tendon loads. Therefore in any structure (beam and one-way slab/joist or two-way flat plate) all tendons in one direction should be placed through or immediately adjacent to a column while the tendons in the other perpendicular direction should be spaced uniformly across the bay width. This requirement to band the strands in one direction and uniformly distribute them in another for the above statically rational reasons also has obvious advantages in the field in that this arrangement simplifies the construction sequence.

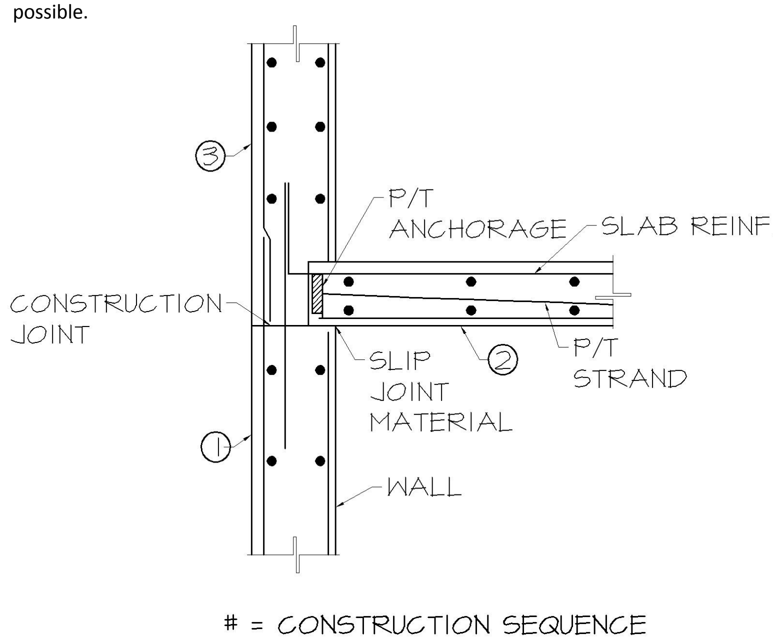
Source: Belfast Valley Contractors

B. At least two of the uniformly distributed tendons should be placed through the column reinforcing cage in a two-way flat plate.

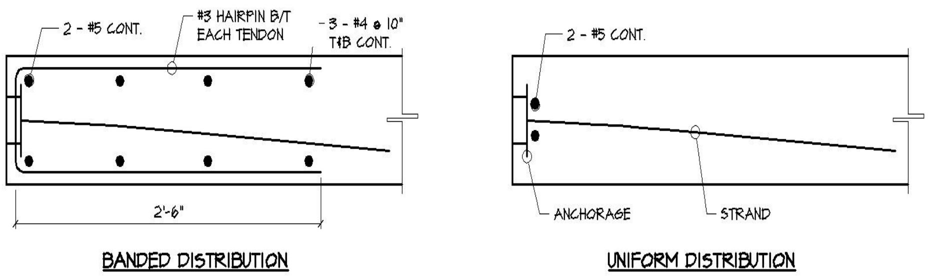
C. Provide conventional bonded reinforcement in the non-compressed zones along the slab edge between the diffusion areas of the end anchorages.



D. Account for volume change (i.e. P/A elastic shortening) and/or avoid restraints where possible.



E. Review live and dead end anchorage arrangements and availability of space as well as confinement reinforcement requirements.



P/T ANCHORAGE DETAILS
(@ SLAB EDGE)

Two-Way Construction Methods:

Originally post-tensioned, two-way slab framing systems were constructed with column and middle strips, similar to those used in conventionally reinforced two-way slabs. However, because the continuous two-way tendons had to be placed in a draped parabolic profile - near the top of the slab at the column lines, and near the bottom of the slab at midspan - the cables had to be placed in a basket weave pattern. This required that the tendons be numbered and installed in a specific sequence. This was difficult, particularly for structures with irregularly spaced column grids.

To avoid the complexities of a basket weave tendon installation, an alternate method of construction was conceived by T.Y. Lin & Associates and Atlas Prestressing Corporation for the infamous Watergate building located in Washington, D.C. in the late 1960s. The system involved banding the tendons - grouping the strands together within a narrow strip - in one direction along the column line grid, while the tendons in the other direction were spaced uniformly above the banded tendons. The banded method of construction resulted in considerable labor savings over the basket weave system, and has become the predominant method for placing post-tensioning tendons in two-way slabs ever since.

The structural adequacy and performance of the banded tendon layout was confirmed through a number of laboratory tests at the University of Texas, Austin in the early 1970s. In addition, the performance of the banded method of construction has also been proven through the continued serviceability of the many buildings that have been erected to date with this method of construction.

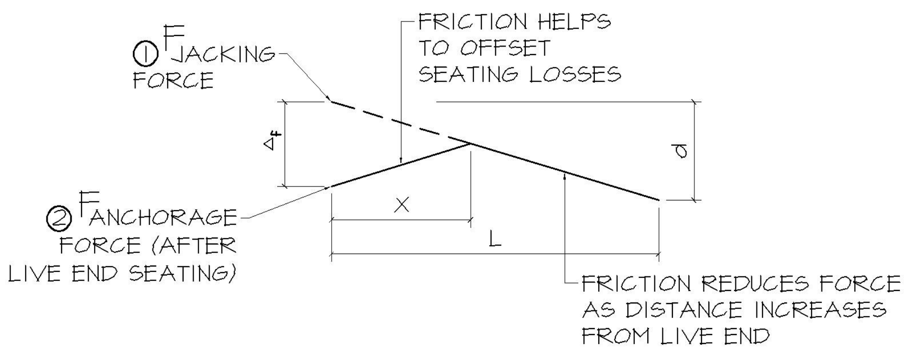
Prestress Losses:

The following table of Prestress Losses is recommended for the design of post-tensioned members, and does not include friction or wedge set losses. Actual losses, whether greater or smaller than computed values, have little effect on the design strength of the member but do affect service load conditions (i.e. deflections, camber, etc.)

Post-Tensioning Tendon Type	Prestress Loss-PSI	
	Slabs	Beams & Joints
Stress Relieved 270K Strand	30,000	35,000
Low Relaxation 270K Strand	15,000	20,000
Bars	20,000	25,000

Friction & Wedge Set Losses:

The diagram on this slide illustrates the impact of friction and wedge set (i.e. anchorage seating) losses on the effective post-tensioning force in a strand.

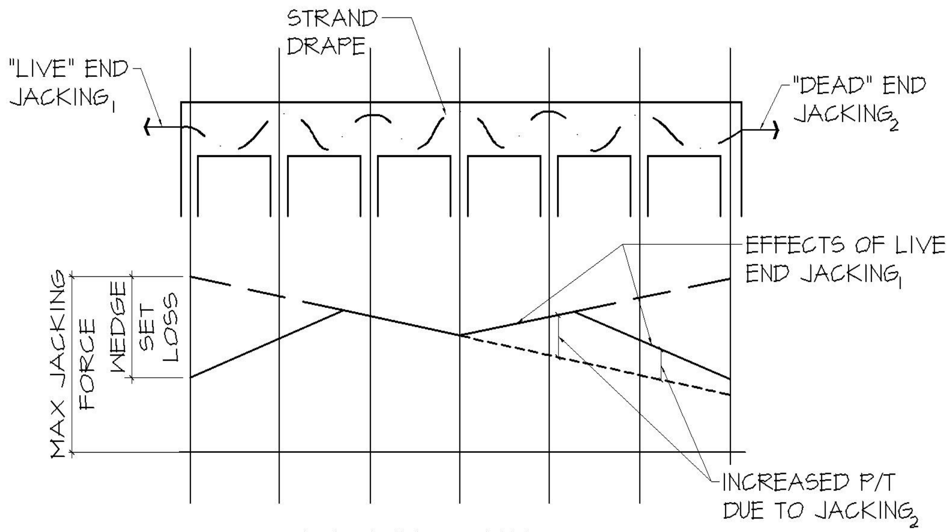


Δf = LOSS OF FORCE DUE TO ANCHORAGE SLIPPAGE/SEATING (ksi)
d = FRICTION LOSS OVER L = LENGTH (ksi & FT)
X = LENGTH INFLUENCED BY ANCHORAGE SEATING (FT)
ΔL = ANCHOR SLIPPAGE (IN)
E = MODULUS OF ELASTICITY (ksi)

E = UNIT STRESS/UNIT STRAIN = $F_{AVE} / \Delta L / X = F_{AVE}\, X / \Delta L$
$F_{AVE} = E \Delta L / X$

FRICTION LOSS & WEDGE SET EFFECTS

The diagram on this slide illustrates how jacking from each end or anchorage of a strand can help to offset friction losses.



FRICTION LOSS EFFECTS
(JACKING FROM BOTH ENDS)

Service Stresses:

Service stress calculations include:

- **Initial** - stresses immediately after transfer of the P/T force, before long-term losses or superimposed loading occurs.
- **Final** - stresses at service loading including long-term losses.

Typically maximum fiber stress in tension controls design. It is my personal experience to design up to the rupture modulus of the concrete thereby avoiding the need to analyze the member as a transformed cracked section (i.e. use Ig).

Other service stress considerations include:

- Minimum P/A = 125 psi for slabs [ACI 314 recommends 200 psi for parking garages]
- Maximum P/A = 500 psi for slabs [ACI 314 recommendation to avoid excessive shortening]

Ultimate Shear Strength:

Shear in both statically determinate and continuous P/T members is affected by the shear carried by the tendons. Essentially the "balancing" load reduces the design shear in a manner similar to that associated with the design moments.

It has been my personal experience to conservatively ignore this contribution of the P/T effects. My rational for this is as follows. First, the allowable shear contribution of the concrete, Vc, permitted by ACI for pretensioned members already accounts for the enhanced characteristics of precompressed concrete. Secondly, from a practical standpoint, more minimum stirrup reinforcement is required in P/T concrete members than conventionally reinforced beams because of the need to provide adequate means of supporting the tendon drape throughout the entire length of the beam. Finally, with two-way flat plate construction, a little conservatism never hurts when it comes to punching shear capacity particularly when you never know when some trade will form or cut a slab opening directly adjacent to the column without first checking with the structural engineer.

Ultimate Flexural Strength:

Important facets of the ultimate strength design of a post-tensioned member include:

- f_{ps} (stress in the post-tensioning strand at nominal flexural strength) is dependent on whether bonded or unbonded tendons are used. This value is lower for unbonded strand.

- A minimum amount of bonded conventional reinforcement is required for unbonded tendons, and is intended to provide control and distribution of cracking at high stress levels. The unbounded reinforcement also assures that the structure will behave as a flexural element rather than a shallow tied arch.

- In almost all cases, the most economical design for flexural strength will utilize the maximum permissible tensile stresses for prestressed concrete.

- ACI code does not provide guidelines for the effective flange width of cast-in-place P/T concrete T-beams. Recommendations are available from PTI and ADAPT. It has been my experience to use the ACI requirements for conventionally reinforced T-beams for the calculation of section modulus for the purposes of service stress analysis with the exception that the gross area of the member be used for the determination of P/A values. In addition, it has been my experience to use the same ACI effective flange width criteria for the calculation of ultimate strength capacities.