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The Construction and Some Aspects of the Design of Post-Tensioned Concrete Buildings

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The Construction and Some Aspects of the Design of Post-Tensioned Concrete Buildings

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COURSE CONTENT

Post-Tensioning

General:

History

A brief history of the development of post-tensioning in this country is provided by the Author in article #7 in the Antiquated Structural Systems series in the December 2008 issue of STRUCTURE Magazine.

Usage

The use of post-tensioning in buildings and other structures encompasses almost every type of concrete structure imaginable. The list of concrete structures and the methods of application include; all types of buildings (commercial, institutional, industrial, distribution, process, parking garages), near-shore and marine facilities, bridges, tanks and vessels, foundations (slabs, mats, rock and soil anchored retaining structures), environmental structures, vehicular barrier cables, cable stays and external strengthening of existing structures. For additional information on the many uses of post-tensioning visit the VSL website at: http://vsl.net/

Advantages

The increased efficiency of post-tensioned concrete members provides a number of advantages over non-prestressed concrete as described below.

1. Reduction in dead load: Post-tensioned concrete members generally contain about 30% less concrete than non-prestressed members designed for equivalent loads and performance.

2. Reduced structural depth: Because of the more efficient use of material, post-tensioned concrete members can provide equivalent or superior performance to non-prestressed members with significantly less structural depth. This reduced structural depth also decreases the building height, and the cost of all of the related components such as cladding, etc.

3. Reduced deflections: In post-tensioned members, most of the dead load produces no deflection. This greatly reduces both instantaneous deflections and long-term deflections caused by concrete creep.

Post-Tensioning Systems:

There are 3 main types of post-tensioning systems in use today; unbonded, bonded and external.

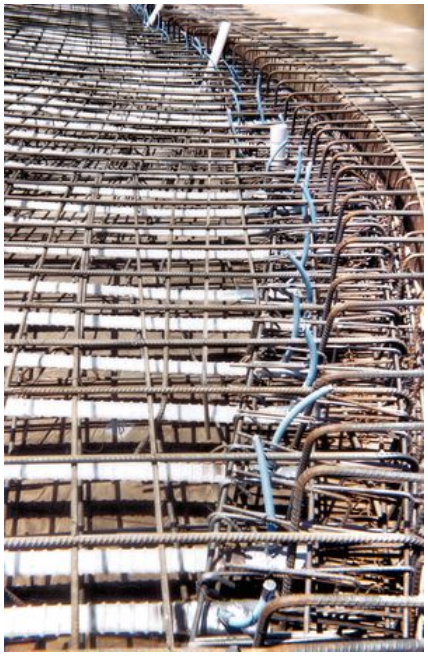
Unbonded

The tendons in an unbonded system typically consist of single-strands (i.e. mono strands) that are coated with corrosion-inhibiting grease and protected by extruded plastic sheathing. The grease allows the strand to move inside the plastic sheathing and prevents moisture intrusion. The strands are anchored to the concrete using ductile iron anchors and hardened steel wedges. The individual, or banded/bundled, tendons are supported by chairs and bolsters along its length to maintain the desired profile.

Unbonded Sheathed Post-Tensioning Strands

Bonded

Bonded post-tensioning systems consist of tendons with multiple strands or bars. The strands or bars are placed in corrugated galvanized steel, high density polyethylene (HDPE) or polypropylene (PP) ducts. Depending on the site conditions and system used, the strands may be installed before the concrete is placed or the ducts may be installed without the strands. The strands are then pulled or pushed through the ducts. Once the concrete has hardened the tendons are stressed and the ducts filled with grout. Inlets and outlets are provided at high and low points to assure that the grout fills the ducts completely.



Bonded Post-Tensioning Strand Ducts

External

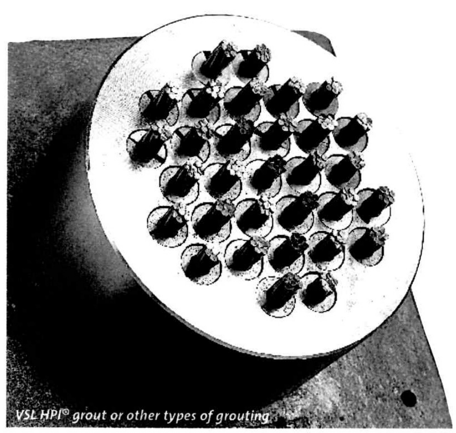
Tendons in an external post-tensioned system are installed outside of the structural concrete member except at anchorages and points of changes in drape or curvature. External tendons can be either straight between anchorages or can run through hold-down blocks to create a draped or harped profile. External tendons are used in bridges, retrofit and repair applications.

Example of External Post-Tensioning Strengthening

Post-Tensioning Components:

Tendons

Post-tensioning systems can generally be divided into three categories; single-strand, multi-strand, or bar, depending on the type of prestressing steel used. The entire assembly of high-strength prestressing steel, end anchorage, and any ducts is referred to as a "tendon." In a single strand post-tensioning system, which is the most commonly used in building construction, the tendon consists of a single, spirally woven 7 wire steel strand, coating, fixed end anchorage, stressing end anchorage, and intermediate anchorage for longer tendons.

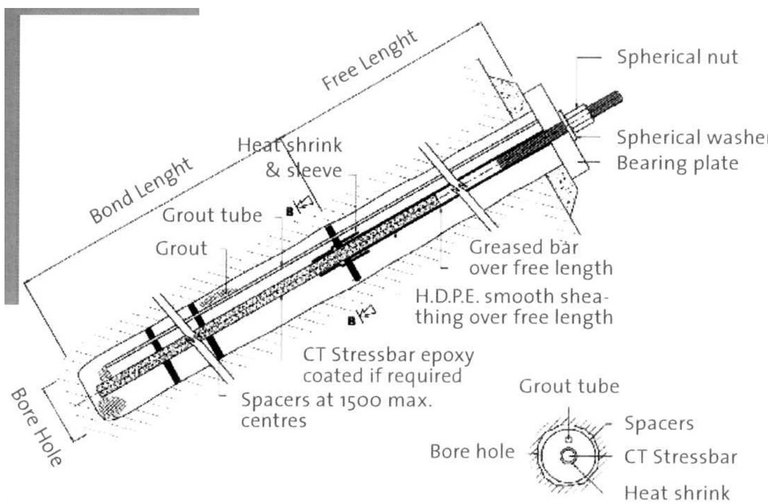


Multi-Strand End Anchorage

Prestressing Steel

The prestressing steel used in a post-tensioning system can be either high strength 7 wire strand or bar. For most prestressing applications, 7 wire strand is used, which consists of helically wrapping six wires around a central straight wire. The diameter of strands supplied in North American typically ranges from 0.375 inches to 0.6 inches. Strands are typically low-relaxation steel with an ultimate tensile strength of 270 ksi. The low-relaxation properties of strand are achieved by a process called stabilizing. This thermo-mechanical process involves stretching the high-strength steel strand to a pre-determined tension and then heating it. This results in a substantial increase in is resistance to relaxation. Almost all of the steel strand produced in North America is low relaxation.

Prestressing bars typically have an ultimate strength of 150 ksi. Diameters of bars range from 0.625 inches to 2.5 inches. Couplers are used to connect bars and lengthen the bar tendons. The types and configurations of bars vary by suppliers. Bar tendons are typically used when short, straight tendons are required.



Post-Tensioned Bar Wall Anchor

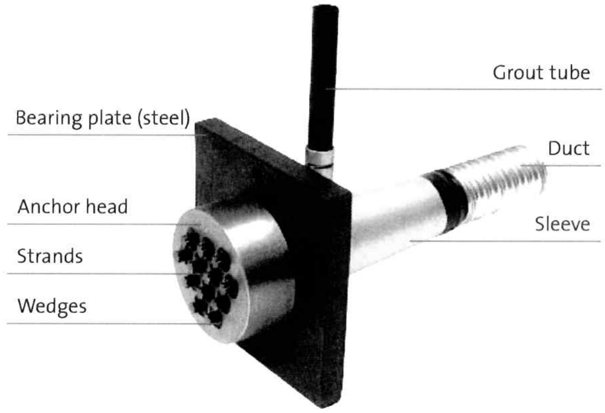
Anchorages

Anchorages are mechanical devices that transmit the tendon force to the concrete. For single strand tendons this includes wedges that grip the strand and a bearing plate that transfers the tendon force directly to the concrete. The following types of single strand anchorages are used;

- Stressing End Anchorages: Stressing end (or live end) anchors are used to stress the strand on site. A pocket former is typically used during the forming and casting operations to embed the stressing anchors in the concrete. After stressing the tendon and confirming that the elongation is within tolerance, the strand "tails" are cut off and the pocket is grouted with non-shrink grout to prevent the intrusion of any moisture.

- Fixed End Anchorages: For unbonded systems, the fixed-end (or dead end) anchorages are typically installed at the fabrication facility before the tendons are shipped to the project site. This involves stressing the tendon to a specified load to set the wedges securely in the anchor (using an initial tensioning force of about 2.0 kips). This ensures that no slippage occurs at the fixed end during the stressing operations. Fixed-end anchorages are used when the tendon is stressed from one end only.

- Intermediate Anchorages: When the tendon is very long, or for staged construction, it may be necessary to provide a construction joint along the length of the tendon. An intermediate anchorage is required to stress the strand at a construction joint.



Multi-Strand, Grouted, Stressing End Anchorage Assembly

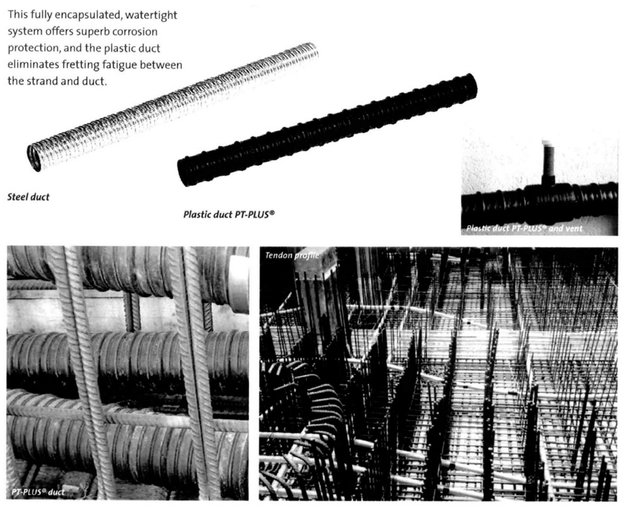
Coatings

Strands in unbonded construction are coated with a corrosion-inhibiting material that typically consists of special grease. The coating is usually applied to the strand as a part of the extrusion process. It acts as a barrier against moisture intrusion, inhibits corrosion of the steel and lubricates the strand so that it can move independently of the surrounding concrete during the tensioning operation.

Ducts/Sheathing

Ducts are used in bonded and, in some cases for external post-tensioning to provide a void that permits the installation and stressing of strands after the concrete has been placed and has hardened. The ducts also provide protection to the post-tensioning strands after construction. Ducts for post-tensioning systems can be either rigid or semi-rigid and are made from ferrous metal, HDPE or PP. Ducts may be round, oval or flat. For bonded post-tensioning, the ducts are corrugated to facilitate the transfer of the post-tensioning force between the tendon and the concrete. In contrast, the ducts for external post-tensioning usually have smooth walls.

The use of HDPE or PP ducts is recommended in corrosive environments. Plastic ducts provide a non-corrosive impermeable barrier between the concrete and the grout. Metallic ducts are usually galvanized to provide a degree of corrosion protection both before and after construction. Galvanized ferrous ducts also provide a barrier to moisture intrusion but are not completely impermeable and may corrode over time in aggressive environments.



Post-Tensioning Ducts

Grout

In bonded construction the ducts containing the strand are filled with cementitious grout as soon as possible after stressing of the tendons. The grout serves several important functions. First the grout bonds the strand to the duct and hence to the surrounding concrete, which facilitates the transfer of force between the tendon and the concrete. Secondly, the grout provides a cementitious cover that protects against any moisture intrusion and corrosion-causing contaminants. Third, the alkalinity of the grout creates a passive environment for steel, further inhibiting corrosion.

Factors Determining the Type of Post-Tensioning System Used:

Strength of Bonded and Unbonded Systems

The compatibility of strain between the concrete and the prestressing steel means that a bonded tendon will develop more force at the design factored load than an unbonded tendon with the same cross-sectional area. To provide an equivalent flexural strength between the two systems, additional bonded non-prestressed reinforcement is normally added to an unbonded post-tensioning system, which supplements the lower post-tensioning force in the unbonded tendon. A minimum amount of non-prestressed reinforcement is also required by ACI 318 when unbonded tendons are used to provide flexural performance and crack control.

Redundancy and Safety of Bonded and Unbonded Tendons

In an unbonded tendon, all of the prestressing force is transferred to the concrete by the anchorages alone. A failure in the unbonded tendon at any point will cause a loss of prestress force throughout the entire length of the tendons between the anchorages. In a bonded tendon, the prestressing force is transferred to the concrete through a combination of bearing at the anchorages and bond with the concrete along the full length of the tendon. A failure in a bonded tendon will reduce or eliminate the prestressing force at the affected section, however, the full post-tensioning force is unaffected beyond the failed area a distance no greater than the full development length of the tendon on either side of the failed section.

Detailing for Post-Tension Construction:

Anchorage Zones

Anchorage zones for post-tensioning tendons are regions of dual responsibility which is shared between the engineer of record and supplier of the post-tensioning system. To prevent errors as a result of simple oversight, the division of responsibility must be clearly defined in the project plans and specifications.

The supplier of the post-tensioning system is usually responsible for the design of the anchorage device and the "local" anchorage zone immediately surrounding the device. The supplementary reinforcement requirements (spirals, etc.) of the local zone relate to the design of the anchorage device itself which in turn involves proprietary technology. The engineer of record is responsible for the design of the "general" zone which surrounds the local zone.

While the design of the local zone is usually standardized for most anchor spacings and clearances, the design of the general zone is different for each application as it depends on the position of the tendon and the overall member geometry. The general design approach used by most post-tension system suppliers is the strut-and-tie method which deals with the primary forces. Other simpler methods are used to analyze spalling forces.

Tendon Curvature

Any time a tendon changes direction it produces "radial" forces on the concrete when it is post-tensioned. The radial forces act in the plane of curvature and equal the tendon force divided by the radius of the curvature. When these forces are overlooked problems such as spalling, cracking and in some cases blowouts can occur. An example detail that shows what type of supplemental reinforcement is used to control the radial forces at a change in plan curvature is illustrated in Figures 1a and 1b below.

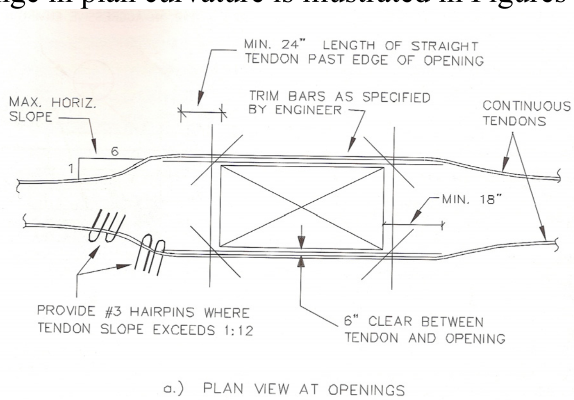


FIGURE 1a

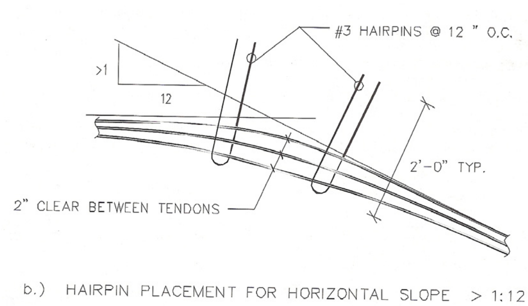


FIGURE 1b

Examples of other typical post-tensioning construction details are provide below.

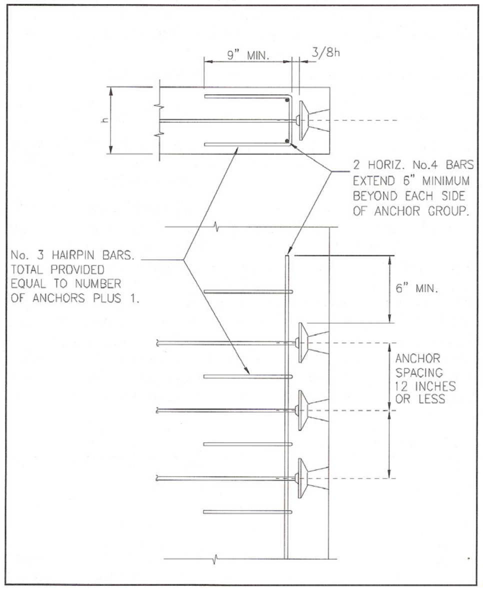


FIGURE 2 (Typical Mono-Strand Live End Anchorage)

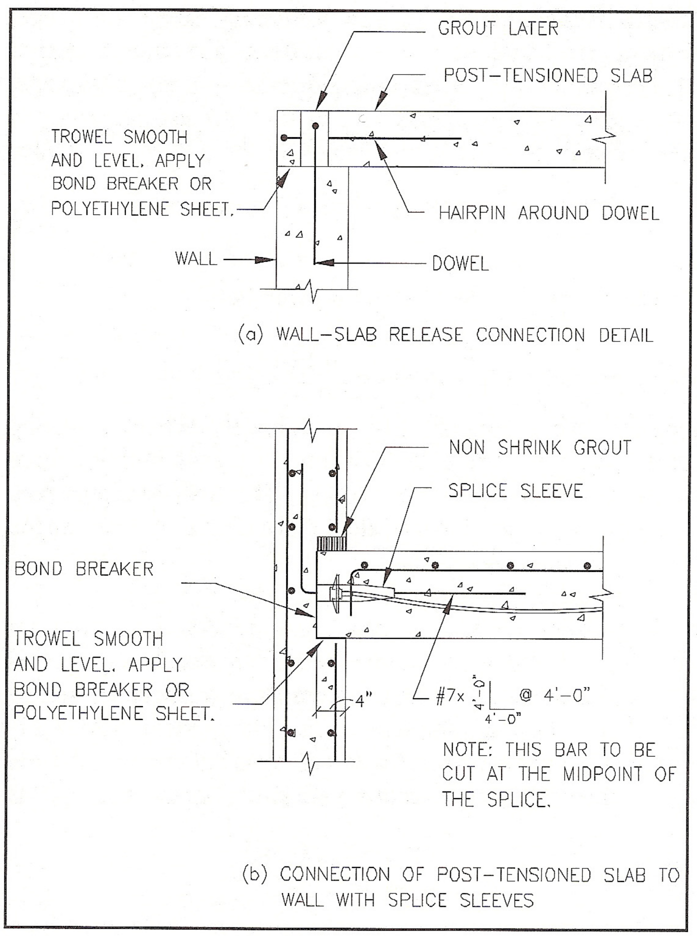


FIGURE 3 (Typical Slip Joint Details at Wall/Slab Intersection)

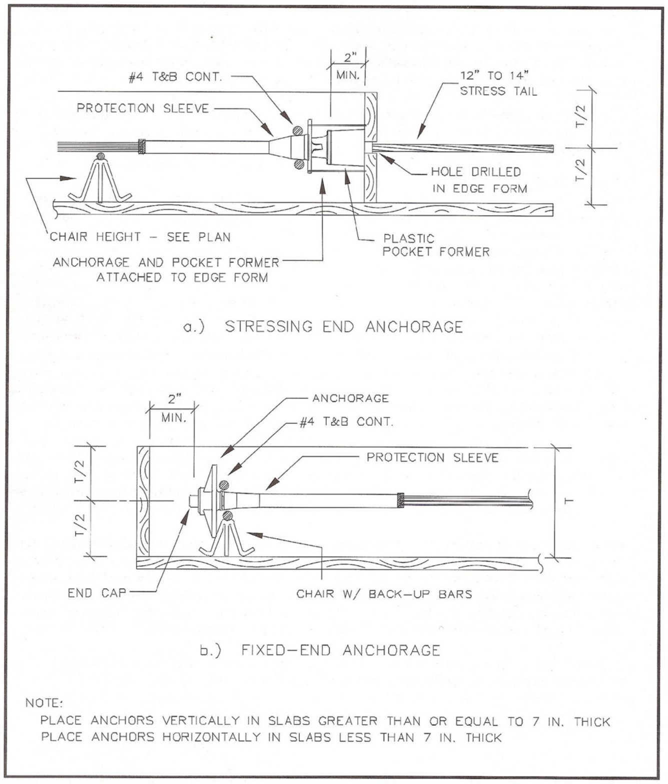


FIGURE 4 (Encapsulated Mono-Strand Details)

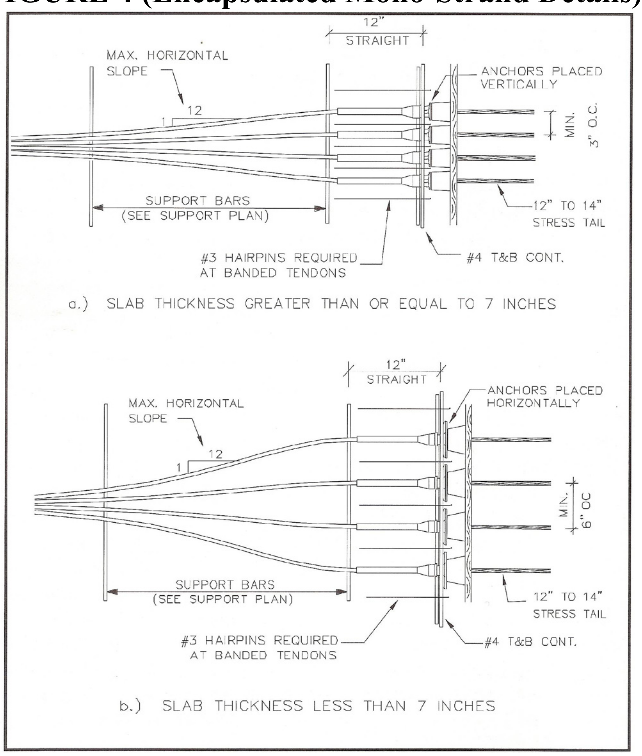


FIGURE 5 (Typical Bundled/Banded Mono-Strand Anchorage Detail)

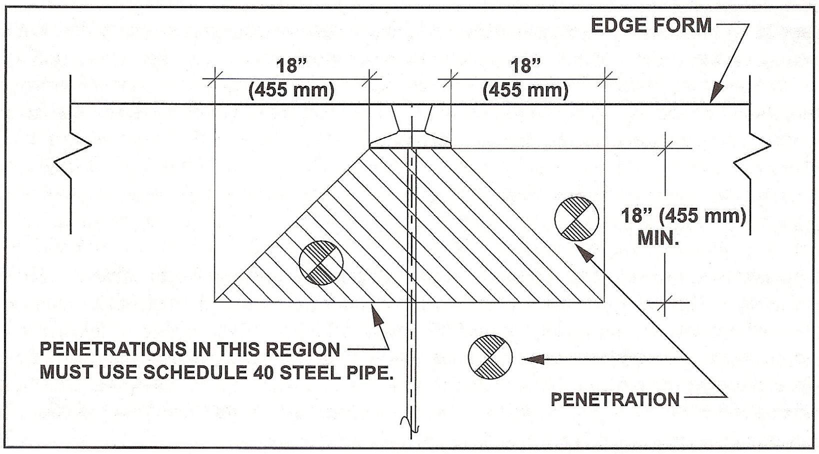


FIGURE 6 (Anchorage Zone Penetration Guidelines)

Grouting:

Advantages

- Provides active corrosion protection: The prestressing steel is actively protected against corrosion through the alkaline environment provided by the cementitious grout.

- Provide permanent bonding of the tendons: Bond allows a significant increase of the prestressing force in a cracked section, and permits the prestressing steel to reach the yield and ultimate strength. This has significant effects on the strength of the section, on the crack distribution in the prestressed member, and on the energy dissipation of the member. Bond has also a very beneficial effect on the redundancy of a prestressed member. A local defect in the tendon does not mean that the post-tensioning force is affected over the entire tendon length.

Grout Properties

- Flowability: This property is considered important in order to assure complete filling of the duct.

- Volume Change: It is considered important to maintain any volume changes of the grout within a specified range to assure that the duct can be properly filled with grout.

- Bleed: It was considered important to limit free water inside the duct to assure that any excess bleed water can be reabsorbed by the grout within a specified time.

- Strength: The strength of grout is an indication of the grout quality with respect to bond and shear strength.

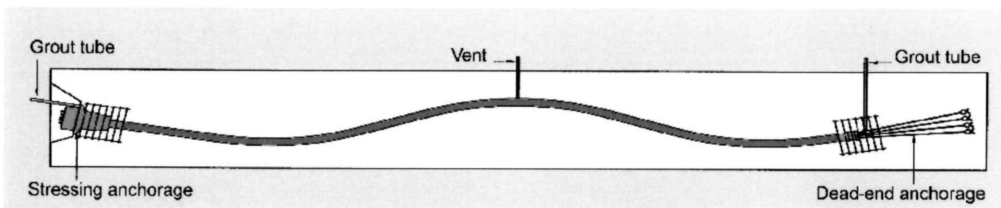
- Resistance to freezing: This property is considered important for applications in exterior cold climates.

Detailing

Correct detailing of the tendon profile, ducts, grout vents (inlet and outlet), connections of the ducts to anchorages, and anchorage caps are very important to assure a high quality grouting operation. For instance, even though the tendon profile is typically chosen for structural reasons to efficiently balance the applied loads, the profile should also be detailed to provide optimum flow of the grout. Local high points where no vents can be placed should be avoided.

The tendon profile needs to be secured with sufficiently strong tendon supports at sufficiently close spacings to avoid inadvertent movements of the duct during the concrete placement operation. In addition, any temporary hole in the duct of an external tendon needs to be properly sealed before grouting to assure reliable corrosion protection.

The ducts also need to have a sufficiently large cross section to allow proper flow of the grout. For strand tendons the duct size is typically chosen such that the cross sectional area of the prestressing steel does not occupy more than 40 to 45% of the duct cross section. For bar tendons, this percentage can be higher. All connections of ducts, vents, anchorages, and caps need to be leak tight to allow for the proper filling of ducts with grout. This is because grouting can only be carried out once the anchor head and anchorage are properly sealed. The most suitable method of sealing anchor heads and anchorages is with the use of temporary or permanent grout caps on the anchorages.



Typical Grouted Duct Arrangement

Procedures

- The grout should be mixed using the appropriately specified water/cement ratio. In addition, the specified sequence of adding water, admixture and cement in the specified grout mixer for the specified mixing time, should be strictly adhered to. As soon as the first mix is ready, the necessary quality control tests should be completed to confirm the specified grout properties. The grouting operation should only commence after the properties of the grout are confirmed.

- The grouting nozzle should be fitted, in general, to the lowest grout connect or to a cable end as specified by the manufacturer.

- Grouting should continue without interruption so that the grout flows continuously in the same direction from the inlet to the cable end. While the grout moves as a solid column in the upward slope of a duct, it will often flow faster downhill than the pump can provide grout. Therefore the grout will have a tendency to fill the descending branch of a duct from the low point backwards up the descending portion of the duct. This condition will likely cause entrapment of air at the high point which needs to be expelled via a vent at the same location. To avoid air entrapment, the maximum rate of flow of grout in the duct should be limited to that recommended by the manufacturer.

- When the grout flows out from the first vent, this same vent is not closed until the grout has a comparable viscosity and consistency as that observed at the mixer. This can be judged visually by experienced personal, and can be confirmed by a grout density test and flow time measurements. If the flow time at the outlet is less than that at the mixer, the difference should not be more than about

3 seconds. Once all of the above is confirmed, the vent connection can then be closed. The same criterion applies for all subsequent vent points, including the outlet in the anchorage cap at the cable end. At all vents, the grout spoils should also be collected for environmental reasons and to avoid staining of the structure.

- If the grouting pressure at the grouting connection approaches that recommended by the manufacturer, the grouting nozzle should be transferred to the next already filled connection and grouting should be continued from there.

- When the entire cable is filled (i.e. when all the vents have been closed) the pump pressure becomes slightly raised. This pressure should be maintained for about one minute. If the pressure can be maintained without significant loss, this can be considered confirmation that the duct system is leak tight. The inlet opening is then also closed. The grouting nozzle can now be removed and fitted to the next cable, however, if the pressure drops significantly, this indicates a leak. Leaks should then be located and sealed, and any voids left should be topped up with grout.

- For long tendons with several high points, vents should be opened again, one after the other, while the grout is under pressure to expel accumulated air and water at high points until the grout exits at the appropriate consistency.

- It is recommended that a grouting report be prepared daily. The report should include all relevant mix data, grout testing results, identification of the grouted tendons, weather conditions and grout consumption. Reporting of grout consumption will allow the detection of gross errors, but will not permit the detection of local voids.

- During the grouting operation, regular quality control test should be performed at the mixer and at the tendon vent farthest away from the mixer. In addition, accessible parts of the tendons should be checked shortly after grouting. All vents and caps should be checked and opened after setting of the grout, and any voids should be filled.

Types of Floor and Roof Systems:

Table 1 provides a suggested span-to-depth ratio for a number of different floor and roof framing systems. Table 1 is applicable for systems in which the live load to dead load ratio is less than 1.0 (i.e. $LL/DL < 1.0$). Tables 2 and 3 provide a summary of one-way and two-way framing systems, respectively. The tables indicate the typical span range and loading for each system.

Floor System	Span/Depth Ratio
One-way slabs	48
Two-way slabs	45
Two-way slab with drop panel (minimum drop panel at least $L/6$ each way)	50
Two-way slab with two-way beams	55
Two-way waffle slab (5 ft × 5 ft grid)	35
Beams, $b \approx h/3$	20
Beams, $b \approx 3h$	30
One-way joists	40

TABLE 1

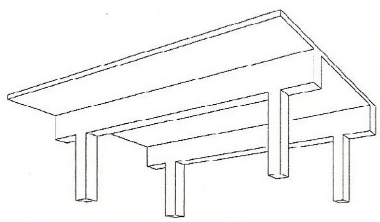
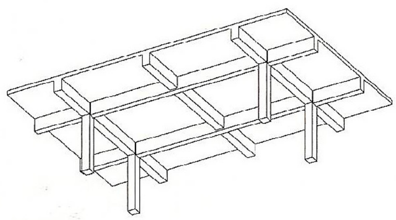
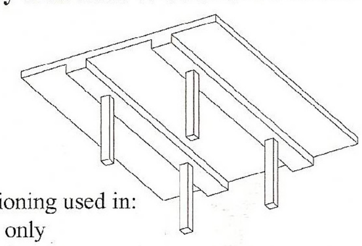
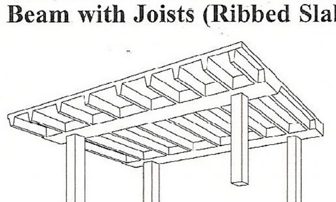
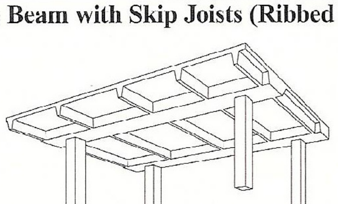
FLOOR SYSTEM AND LAYOUT OF POST-TENSIONING TENDONS	Typical span range (column center-to-center)	TYPICAL LOADING	COMMENTS
One-Way Slab and Beam  Post-tensioning used in: Beams, slabs (main and temperature)	Beams = 50 to 65 ft (15 to 20 m) Slabs = 15 to 30 ft (4.5 to 9 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Commonly used in parking structures but has also been used effectively in office buildings with long spans • Specialized forming systems have been designed for this system (steel beam forms and large-panel slab forms)
Slab, Beam, and Girder System  Post-tensioning used in: Slabs (main and temperature), beams and girders	Slabs = 15 to 20 ft (4.5 to 6 m) Beams = 50 to 65 ft (15 to 20 m) Girders = 30 to 40 ft (10 to 12 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Generally more economical than spanning a very thick slab between beams located on column lines • Commonly used in parking structures at "turn-around" aisles and in other occupancies with short-direction spans of 30 ft and more
One-Way Slab Plus Wide Shallow Beam  Post-tensioning used in: a. Beams only b. Slab only c. Beams and slab	Beams = 25 to 40 ft (8 to 12 m) Slabs = 18 to 25 ft (5.5 to 7.5 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Effective for column layouts with short span in one directions and long span in orthogonal direction • Normally beams span long direction, slab spans short direction • Used primarily where structural depth is limited
Wide Beam with Joists (Ribbed Slab)  Post-tensioning used in: Beams and joists *Note: Beams and joists should have the same depths.*	Slabs = Typically about 3 ft (1 m) Beams = 20 to 35 ft (6 to 11 m) Joists = 35 to 65 ft (11 to 20 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Effective for column layouts with short span in one directions and long span in orthogonal direction • Normally beams span short direction and joists spans long direction • Minimized structural depth
Wide Beam with Skip Joists (Ribbed Slab)  Post-tensioning used in: Beams and joists, occasionaly in slab *Note: Beams and joists should have the same depths.*	Slabs = Typically about 3 to 12 ft (1 to 4 m) Beams = 20 to 35 ft (6 to 11 m) Joists = 35 to 55 ft (11 to 17 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Spreads joists as far as possible without increasing cost of slab • Often allows more eficient use of post-tensioning in joists (force per foot of width

TABLE 2

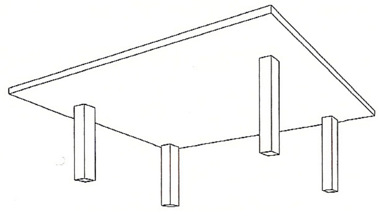
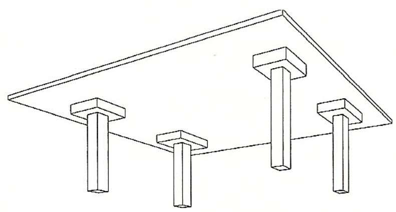
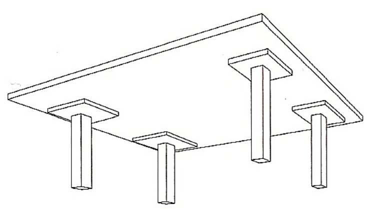
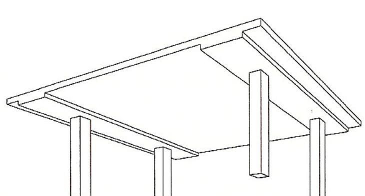
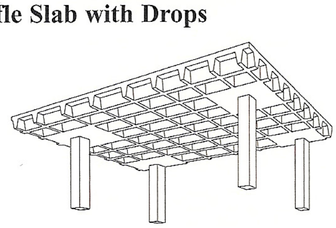
FLOOR SYSTEM AND LAYOUT OF POST-TENSIONING TENDONS	Typical span range (column center-to-center)	TYPICAL LOADING	COMMENTS
Flat Plate  Bands in one direction, and uniformly distributed tendons in the other	20 to 30 ft (6 to 9 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Lowest formwork cost • Flexibility in column arrangement • Flat ceiling • Greatest flexibility in under-ceiling services layout • Most efficient if bay size is approximately square • Load path easy to visualize • Punching shear strength can be increased using studrails, shearheads, or conventional shear reinforcement
Flat Slab with Column Capitals  Bands in one direction, and uniformly distributed tendons in the other	25 to 35 ft (8 to 11 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Effective system for increasing punching shear capacity if architectrual considerations permit • Small caps have minor effect on flexural behavior
Flat Slab with Drop Panels  Bands in one direction, and uniformly distributed tendons in the other	30 to 40 ft (9 to 12 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Larger drop panels can be effective in reducing flexural reinforcement • Normally used for longer spans
Slab with Slab Band  Bands in one direction, and uniformly distributed tendons in the other	25 to 40 ft (8 to 14 m)	Light: Up to 100 psf (5 kN/m^2) to Medium: 100 to 200 psf (5 - 10 kN/m^2)	• Can be very effective in panels with rectangular aspect ratios • Two-way behavior must be justified to avoid more restrictive one-way code requirements
Waffle Slab with Drops  Ribs both ways *Note: Ideally the "drops" and "ribs" have the same depth.*	30 to 60 ft (9 to 18 m)	Medium: 100 to 200 psf (5 - 10 kN/m^2) to Heavy: over 200 psf (10 kN/m^2)	• Very effective for heavy loading and relatively long spans • Most efficient if bay size is approximately square

TABLE 3

Miscellaneous Methods of Post-Tension Construction :

As was indicated at the beginning of this lecture, post-tensioning is also used in a wide variety of structures besides floor and roof framing in buildings. Figure 7 below shows the use of unbonded, banded, mono-strand in a large foundation mat. It is interesting to note that the strand drape is low at the column locations and high between the columns, completely opposite of what one would see in an elevated framed slab. This is because in a mat, due to the upward uniform soil bearing pressure, the concrete must resist negative moments at the midspan and positive moments at the columns.

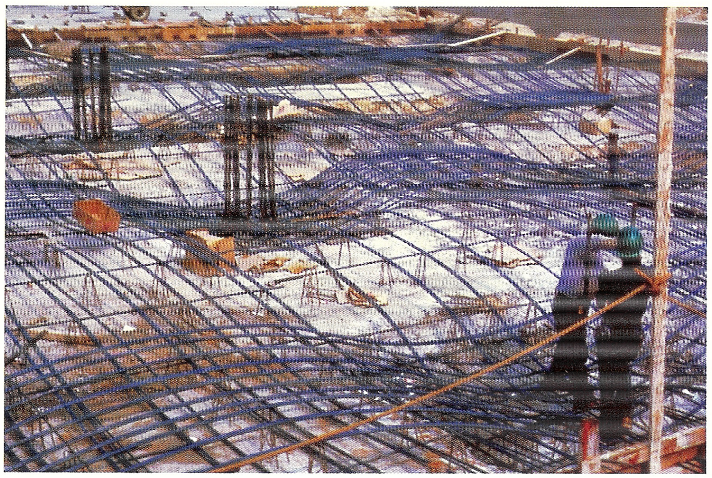


Figure 7

As was indicated earlier, unbonded tendons are susceptible to detensioning if they are damaged over the life of the building. Damage to the tendons typically occurs during the installation of suspended equipment and architectural appurtenances when impact drills are used to install the required hanger inserts. Since the location of the tendons is difficult to establish once the building envelope is erected and the anchorage locations around the perimeter of the building cannot be seen, damage to unbonded tendons occurs on a frequent basis. One technique used to identify the location of the tendons on the bottom of the structure is to mark the strand locations on the soffit form with paint prior to placing the concrete. The paint is partially absorbed by the concrete so that the location of the tendons can be identified at a later date. An example of this technique is shown in Figure 8 below.

FIGURE 8

Another interesting use of post-tensioning strands is for barrier cable systems. Chapter 16 of the PTI Design Manual includes the design criteria for barrier cables using post-tensioning strand.

Fire Resistance:

Similar to the discussion of fire resistance for conventionally reinforced concrete systems, the fire rating of post-tensioned structures is also related to the type of aggregate, the concrete cover and whether the construction can be considered restrained or unrestrained. Table 4 provides a summary of the minimum slab thickness required to provide 1, 2, 3 and 4 hour fire resistance based on the type of aggregate used. Table 5 provides a summary of the minimum concrete cover required to provide 1, 2, 3 and 4 hour fire ratings for various post-tensioned systems.

For post-tensioned construction, end spans are considered to be unrestrained and interior spans are considered to be restrained. For two-way slabs, this criteria is dependent of the direction of the reinforcement in each orthogonal direction. Therefore, for an unrestrained end bay in a two-way slab tendons running parallel to the slab edge do not require an increased fire cover until they reach their own end bay.

Aggregate Type	1 hr	2 hr	3 hr	4 hr
Siliceous	3.5 in.	5.0 in.	6.2 in.	7.0 in.
Carbonate	3.2 in.	4.6 in.	5.7 in.	6.6 in.
Sand-lightweight	2.7 in.	3.8 in.	4.6 in.	5.4 in.
Lightweight	2.5 in.	3.6 in.	4.4 in.	5.1 in.

TABLE 4

Restrained / Unrestrained	Type of P/T Structure	1 hr	2 hr	3 hr	4 hr
Unrestrained	Solid Slab(1)	---	1½ in.	2 in.	---
Unrestrained	Beams & Girders 8 in. Wide(3)	1¾ in.	2½ in.(2)	4½ in.	---
Unrestrained	Beams & Girders > 12 in. Wide(3)	1½ in.	---	2½ in.	3 in.
Restrained	Solid Slab(1)	---	¾ in.	1 in.	1¼ in.
Restrained	Beams & Girders 8 in. Wide(3)	---	1¾ in.	2 in.	2½ in.
Restrained	Beams & Girders > 12 in. Wide(3)	---	1½ in.	1¾ in.	2 in.

(1) For solid slabs of siliceous aggregate concrete, increase tendon cover 20%

(2) Two layers of equal thickness with a ¾ in. air space between

(3) For widths between 8 and 12 in., interpolation shall be permitted

TABLE 5

Post-Tensioning Losses:

A significant factor which must be considered in the design of post-tensioned members is the loss of prestress due to various causes. These losses can dramatically affect the behavior of a member at service loads. Although calculation procedures and certain values of creep strain, friction factors, etc., are recommended, they are at best only an estimate. Never the less, establishing the appropriate magnitude of losses is vital not only for the design of the structure but also to properly document the required magnitude and location of the post-tensioning forces as required by ACI Section 1.2.1(g).

Lump sum values of post-tensioning losses were widely used up through the 1983 ACI Code, however, this approach is now considered obsolete by ACI. This is because lump sum values have been found to be obsolete for some design conditions. Table 6 provides a summary of these lump sum values. Because the basis of the following methods of calculating the various components associated with post-tensioning losses was developed starting in 1979, prior to the 1983 ACI Code, it is my personal preference to use the lump sum values, when they are deemed appropriate for a given project design. This approach is also in line with the recommendations of the PTI which states that "any reasonable estimate of losses is acceptable."

Post-tensioning tendon material	Prestress loss — psi	
	Slabs	Beams and Joists
Stress relieved 270k strand and stress relieved 240k wire	30,000	35,000
Bar	20,000	25,000
Low relaxation 270k strand	15,000	20,000

* Note: This table of approximate prestress losses was developed to provide a common Post-Tensioning Industry basis for determining tendon requirements on projects in which the magnitude of prestress losses is not specified by the designer. These loss values are based on use of normal weight concrete and on average values of concrete strength, prestress level, and exposure conditions. Actual values of losses may vary significantly above or below the Table values in cases where the concrete is stressed at low strengths, where the concrete is highly prestressed, or in very dry or very wet exposure conditions. The Table values do not include losses due to friction.

TABLE 6

Elastic Shortening of Concrete

For members with unbonded tendons, the elastic shortening (ES) of concrete can be computed as indicated below. ES is considered an immediate short time loss which occurs as a result of the elastic response of the concrete to the application of the post-tensioning force.

$ES = K_{es}E_s(f_{cpa}/E_{ci})$

Where; K_{es} = 0.5 for post-tensioned members where the tendons are tensioned in sequential order to the same tension. For other post-tensioning procedures K_{es} may vary from 0 to 0.5.

E_s = Modulus of Elasticity of the Post-Tensioning Steel; typically = 28,000 ksi

f_{cpa} = Average compressive stress in the concrete along the member length at the center of gravity of post-tensioning steel immediately after the post-tensioning forces have been applied to the concrete.

E_{ci} = Modulus of Elasticity of concrete at time post-tensioning is applied.

Creep of Concrete

For members with unbonded tendons, the long-term volume change effects of concrete creep (CR) can be computed as:

$CR = K_{cr}(E_s/E_c)(f_{cpa})$

Where: K_{cr} = 1.6 for post-tensioned members

E_c = Modulus of Elasticity of concrete at 28 days.

Shrinkage of Concrete

The long-term volume can effects of concrete shrinkage (SH) can be computed as:

$SH = (8.2 \times 10^{-6)} K_{sh} E_s(1 – 0.06(V/S))(100\text{-}RH)$

Where: K_{sh} – See Table 7

RH = Average relative humidity surrounding the concrete member.

V/S = Volume to surface ratio, usually taken as the gross cross sectional area of the concrete member divided by its perimeter.

Time, days*	1	3	5	7	10	20	30	60
K_{sh}	0.92	0.85	0.80	0.77	0.73	0.64	0.58	0.45

Time after end of moist curing to application of prestress

TABLE 7

Relaxation of Tendons

The long-term effects of tendon relaxation (RE) can be computed as:

$RE = (K_{re} – J(SH + CR + ES))C$

Where: K_{re} – See Table 8

J – See Table 8

C – See Table 9

Type of Tendon	Kre (psi)	J
270 Grade stress-relieved strand or wire	20,000	0.15
250 Grade stress-relieved strand or wire	18,500	0.14
240 or 235 Grade stress-relieved wire	17,600	0.13
270 Grade low-relaxation strand	5000	0.040
250 Grade low-relaxation wire	4630	0.037
240 or 235 Grade low-relaxation wire	4400	0.035
145 or 160 Grade stress-relieved bar	6000	0.05

TABLE 8

f_{pi}/f_{pu}	Stressed relieved strand or wire	Stress-relieved bar or low relaxation strand or wire
0.80		1.28
0.79		1.22
0.78		1.16
0.77		1.11
0.76		1.05
0.75	1.45	1.00
0.74	1.36	0.95
0.73	1.27	0.90
0.72	1.18	0.85
0.71	1.09	0.80
0.70	1.00	0.75
0.69	0.94	0.70
0.68	0.89	0.66
0.67	0.83	0.61
0.66	0.78	0.57
0.65	0.73	0.53
0.64	0.68	0.49
0.63	0.63	0.45
0.62	0.58	0.41
0.61	0.53	0.37
0.60	0.49	0.33

TABLE 9

Friction and Wedge Set

Friction and wedge set are immediate short term losses that occur directly as the result of the post-tensioning operation. Friction losses result because of the restraint between the strand and the sheathing or duct. Friction is a function of the length of the tendon and the extent of vertical and horizontal drape, or change in curvature. Wedge set, or seating loss, occurs as a result of the physical movement of the wedges into the anchorage as the jacking force is released. Wedge set results in about 0.25 or 0.375 inch of travel (or loss of elongation and subsequently tension) of the strand during the seating operation.

Wedge set losses at the dead end anchorage do not have to be accounted for because the strands are typically pretensioned and pre-seated at the factory prior to shipment to the field. Frictional restrain of the strand, which reduces the amount of effective force in the tendon as the cable gets further away from the live jacking end, actually serves to limit the extent of impact of the live end wedge set loss. The amount of frictional and wedge set losses assumed in the design can be checked via a comparison of the actual field elongation and calculated elongation; PL/AE.

Frictional losses are calculated as indicated below. Values for the coefficients used in the formulas for friction loss, T_x, are provided in Table 10.

The friction along a cable is calculated according to the formula:

$$T_x = T_o e^{-(\mu\alpha + kx)} \quad (1)$$

Or if ($\mu\alpha + kx$) is not greater than 0.15, according to the following simplified formula:

$$T_x = \frac{T_o}{1 + \mu\alpha + kx} \quad (2)$$

Where:

T_x = prestressing force at point x
T_o = prestressing force at jacking end
e = base of Naperian logarithms
μ = curvature friction coefficient
α = total angular change in radians from jacking end to point x
k = wobble friction coefficient per ft of tendon
x = length of cable from jacking end to point x in feet

Type of Duct	Range of Values		Recommended for Calculations*	
	μ	k	μ	k
Flexible tubing non-galvanized	0.18 – 0.26	$5-10\times10^{-4}$/ft	0.22	7.5×10^{-4}/ft
Flexible tubing galvanized	0.14 – 0.22	$3-7\times10^{-4}$/ft	0.18	5.0×10^{-4}/ft
Rigid thin wall tubing non-galvanized	0.20 – 0.30	$1-5\times10^{-4}$/ft	0.25	3.0×10^{-4}/ft
Rigid thin wall tubing galvanized	0.16 – 0.24	$0-4\times10^{-4}$/ft	0.20	2.0×10^{-4}/ft
Greased and wrapped	0.05 – 0.15	$5-15\times10^{-4}$/ft	0.07	10×10^{-4}/ft

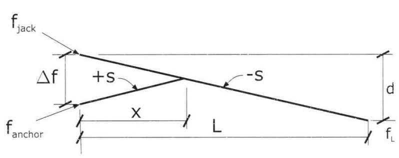
* Practice has shown that friction losses can vary from case to case. The recommended values given above are suggested for calculating the friction losses but in some instances the extreme values should also be considered.

TABLE 10

The method used to determine the effects of wedge set loss is provided below.

A.2 DERIVATION OF FORMULAS FOR CALCULATING THE EFFECTS OF ANCHOR SET

The effects of anchor set on tendon stresses may be calculated with sufficient accuracy for most conventional applications in accordance with the diagram and formulas presented below.



Δf = Change in stress due to anchor set, ksi
d = Friction loss in length, L, ksi
x = Length influenced by anchor set, ft
L = Length to point where loss is known, ft
ΔL = Anchor set, in.
E = Modulus of elasticity, ksi

$$E = \frac{\text{Unit Stress}}{\text{Unit Strain}} = \frac{f_{avg}}{\Delta L / x} = \frac{f_{avg}\,x}{\Delta L}$$

$$f_{avg} = \frac{E\,\Delta L}{x}$$

$$\frac{\Delta f}{2} = \frac{E\,\Delta L}{12\,x} \qquad \text{Units Correct}$$

$$\Delta L = \frac{P_{avg}\,x}{A\,E} = \frac{f_{avg}\,x}{E}$$

$$f_{avg} = \frac{E\,\Delta L}{12\,x}$$

$$\frac{\Delta f}{2} = \frac{E\,\Delta L}{12\,x} \qquad \text{Units Corrected}$$

$$\Delta f = \frac{E\,\Delta L}{6\,x} \qquad \Delta L \;\&\; x \text{ known}$$

By Similar Triangles:

$$\frac{x}{\Delta f / 2} = \frac{L}{d}$$

$$\Delta f = \frac{2\,x\,d}{L} \qquad x \text{ known}$$

$$x = \frac{E(\Delta L)L}{6\,x \times 2\,d}$$

$$x^2 = \frac{E(\Delta L)L}{12\,d}$$

$$x = \sqrt{\frac{E(\Delta L)L}{12\,d}} \qquad \Delta L \text{ known}$$

Also from $\Delta f = \dfrac{E\,\Delta L}{6\,x}$ & $\Delta f = \dfrac{2\,x\,d}{L}$

$$x = \frac{E\,\Delta L}{6\,\Delta f} = x = \frac{L\,\Delta f}{2\,d}$$

$$\Delta f^2 = \frac{E\,\Delta L\,d}{3\,L}$$

$$\Delta f = \sqrt{\frac{E\,\Delta L\,d}{3\,L}} \qquad \Delta L \text{ known}$$

When measuring anchor set, the tendon elongation within the jack must be considered:

Assume the jacking force to be $0.8f_{pu}$

$= 0.8 \times 270 = 216$ ksi

Anchor set is typically assumed to be ¼ in.

Assume the length of stressing jack to be 4 ft-0 in.

$E = 28.5 \times 10^3$ ksi

Elongation of tendon within the jack:

$$\Delta L_{jack} = \frac{216 \times 4 \times 12}{28.5 \times 10^3} = 0.36 \text{ in.}$$

Total elongation lost during anchor set:

= elongation within the jack + anchor set

= 0.36 in. + 0.25 in. = 0.61 in.

Due to the cumulative effects of frictional loss on long continuous strands, it is sometimes necessary to jack the cable from each end. The effects of this type of procedure, as represented by a generic friction and wedge set loss graph, is provided in Figure 9.

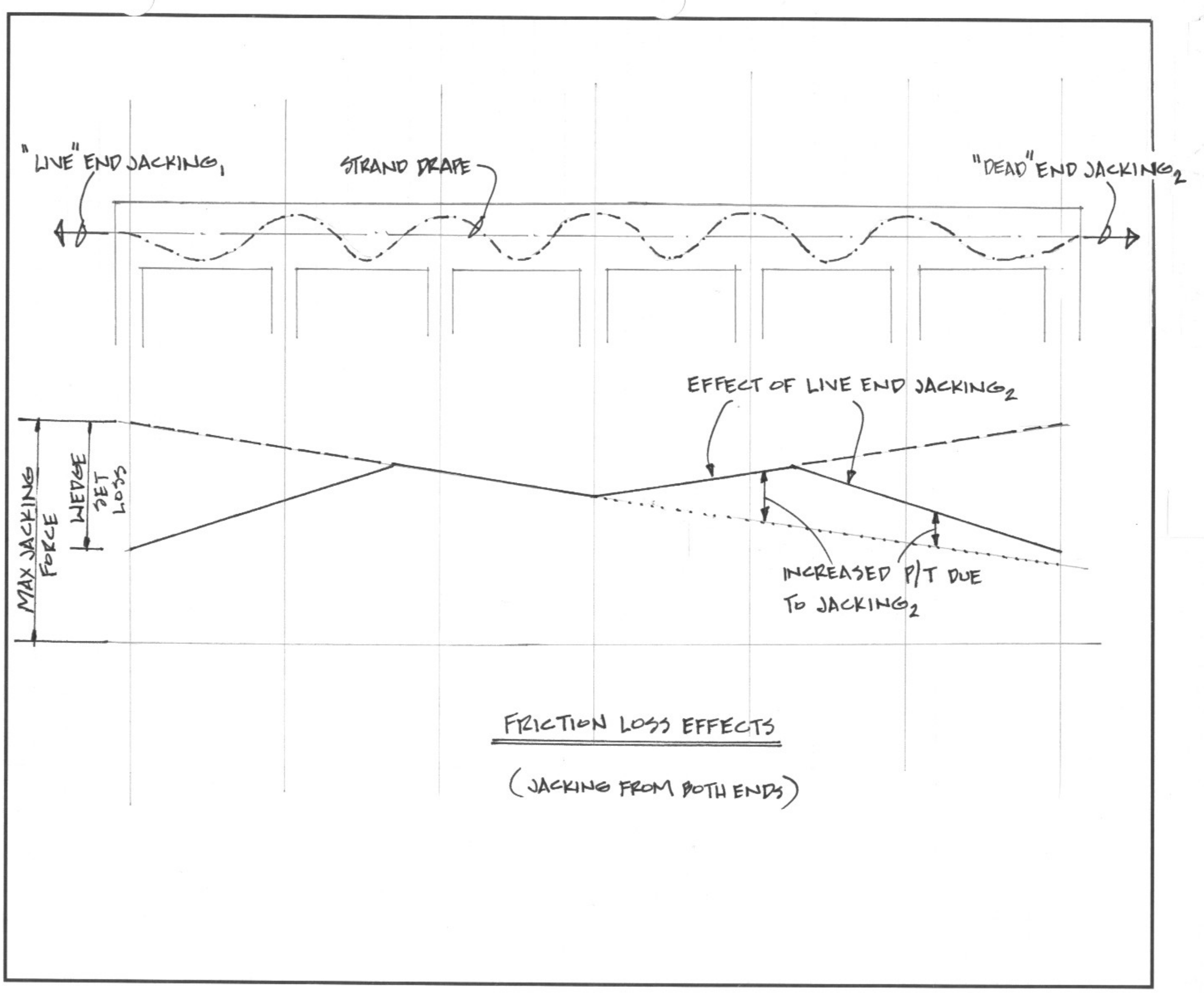


FIGURE 9

The command statements for a program (PTL – Post Tension Loss) that is capable of calculating the combined effects of friction loss, wedge set loss, and the other long and short term losses described above using the lump sum approach are available from the Author upon request. This program also calculates the balancing load for one strand (i.e. a virtual balancing load) and the strand location at critical locations along the span for both beams and slabs.

General Introduction to Post-Tensioned Concrete Design:

Definitions

Prestressed concrete pertains to a structural member that is compressed via tensioned tendons prior to application of any external loads. There are two types of prestressed concrete members:

- Pretensioned: The tendons are stressed prior to casting of the concrete. This is accomplished by first tensioning the strands and anchoring them to either external abutments or self-stressing forms prior to transfer of the prestressed force to the hardened concrete. The tensioning force is imparted by releasing the strands from the temporary anchors, which transfers the force directly into the concrete over the entire length of the cable. Therefore pretensioned concrete involves bonded strands only because the force is transferred to the concrete via mechanical bond between the stranded wires and the surrounding concrete.

- Post-Tensioned: The tendons are stressed after the concrete is cast and has hardened. The strands are anchored against the concrete member after the tensioning operation. Strands are typically unbonded (i.e. anchored only at the ends via anchorage assemblies) but can subsequently be bonded to the concrete (i.e. stressed in ducts and grouted in place).

Design Philosophy

The eccentricity of the tensioned cables, relative to the neutral axis of the member, produces internal moments that act in opposition to the moments induced by external gravity loads. In addition, pre-compression of the concrete (i.e. P/A) also helps to control cracking and other serviceability issues. Typically the required prestressing force (i.e. the number, size and profile of the tendons) is determined by service stress conditions in which:

$$f_b = (P/A \pm M_{Net}/S) \leq f_{Allowable}$$

$$\text{Where: } M_{Net} = ((M_{DL} + M_{LL}) - M_{Balancing})$$

Once the service stress conditions have been met, the ultimate flexural and shear strength of the section are checked at the required critical points. Changes in the number of strands are made or addition conventional bonded reinforcing is added as required to satisfy ultimate strength requirements.

Placement and Details

The following items should be considered when laying out and detailing the tendons in a post-tensioned member.

1. Tendons at the high points that join adjacent draped strand profiles exert downward reactions. The tendons should therefore 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 (beams and one-way slabs/joists 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. Tendons, in general should be banded parallel to the longest panel span and uniformly spaced parallel to or in the direction of the shortest panel span.

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

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

4. Account for volume changes in the concrete (i.e. P/A elastic shortening) and/or avoid restraints where possible.

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

6. Review the need for pour strips due to the length of tendon, likely construction joint sequencing or lack of accessibility around the perimeter of the pour.

Analysis

Preliminary Sizing of Members and Tendon Drape:

The recommended span-to-depth ratios provided above for the various different types of floor and roof framing systems, or experience, are typically used to establish the preliminary member sizes initially used in the design process. The selection of the required drape of the strand is more of an art form than science, however, it is still an intuitive process that is picked up fairly quickly as one becomes accustomed to the nuisances of the load balancing method.

Typically tendons are located near the bottom fiber at positive moment regions and near the top fiber at negative moment regions. This is accomplished by laying out the tendon position with the maximum drape low and high points corresponding to these same critical locations, respectively, within the span of the member. Exceptions to this rule include the need to anchor the tendons at the neutral access of an exterior end support condition. These means that for a flat plate or flat slab the tendons must be anchored at mid-depth of the slab edge. In addition, the variability of adjacent spans lengths or loading conditions will also have an impact on the final tendon geometry. The different types and arrangements of tendons used in buildings include:

- Bonded (typical used only at transfer girders or in structures exposed to severe environments)
- Unbonded (more commonly used in buildings than bonded tendons)
- Parabolic Drape (more commonly used in buildings than straight line drape)
- Straight Line (typically only used in pretensioned members)
- Horizontal Sweep (used at slab openings and where adjacent columns do not align on a orthogonal grid)

Primary and Secondary Moments:

In simple span beams the primary post-tensioning moments induced by the prestressing force (P) are directly proportional to the eccentricity (e) 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 eccentric post-tensioning force is restrained where it is continuous over other supporting members within the structure (see Figure 10).

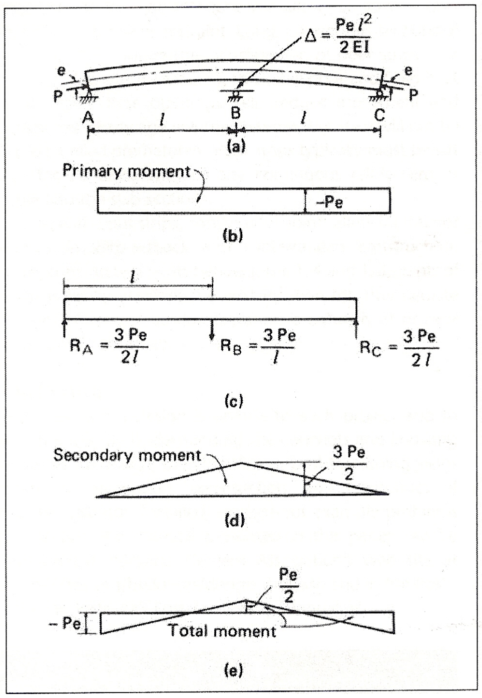


FIGURE 10

This restraint modifies the reactions and therefore affects the elastic moments and shears resulting from the post-tensioning 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 moment (Pe) and not because they are negligible or necessarily smaller than the primary moment. It is also important to note that secondary moments are functions of the reactions and therefore vary linearly between supports. In addition, the total post-tensioning moment is equal to the super-position of the primary moment (Pe) and secondary moments.

In most continuous structures secondary moments have the effect of increasing the magnitude of the positive post-tensioning moment at interior supports and reducing the negative post-tensioning moment between supports. ACI 318-05 Section 18.10.3 requires that the secondary moments (using 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:

Methods of analysis used in the design of post-tensioned structures include:

1. Area Moment Method

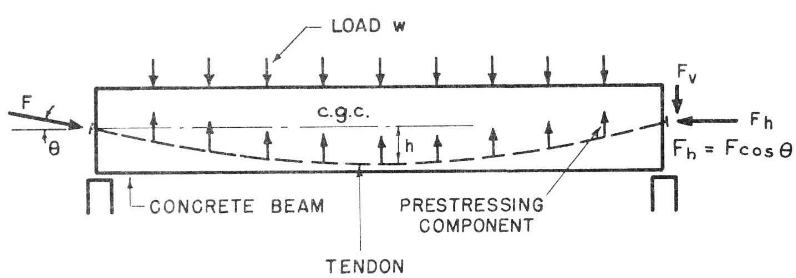
2. Equivalent Load Method

3. Load Balancing Method: This method was introduced by T.Y. Lin in June 1963. The basic concept of load balancing involves the representation of the influence of tendons by using equivalent upward loads. This method is by far the most convenient and common method of analysis used today and is recommended by PTI.

The load balancing method (see Figure 11) involves the selection of a magnitude of prestressing force that "balances" or counteracts some portion of the imposed gravity 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 moment (Pe) from the moments caused by the balancing load at any location along the beam.

The initial portion of any post-tensioning 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. A number of engineers like to think in terms of a percentage of dead or live load that is balanced as the 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 then determine the balancing load for one strand (i.e. a virtual load) taking into account friction, wedge set and other losses. This initial balancing load is then used in the preliminary service stress analysis. From these initial results adjustments to the strand drape and jacking sequence are made as necessary to obtain satisfactory service stress analysis results.

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 and flat slab construction) the effects of the actual tendon profile over the supports relative to that assumed by the balancing load analysis result in errors in the magnitude of only 5% to 10%. As the calculated load balancing moments only directly effect the service stress calculations more so than the ultimate strength results, the load balancing method is therefore sufficiently accurate in most cases, without consideration of the reverse tendon curvature over the supports.



FOR PARABOLIC CABLE WITH SMALL SAG h, SPAN L, LOAD w

$$F = F_h = \frac{wL^2}{8h}$$

FIGURE 11

Service Stress:

The investigation of service load conditions involves an elastic theory approach (i.e. the linear variation of stress with strain). The service stress investigation of post-tension members includes both a check of the initial stresses immediately after tensioning and the final stresses that occur as a result of the application of all imposed loads.

- Initial Service Stress: For conditions immediately after post-tension force transfer, Section 18.4.1 of ACI 318-05 allows a maximum extreme fiber compressive stress of $0.60f'_c$ and extreme fiber tensile stress of $3(f'_c)^{1/2}$, except $6(f'_c)^{1/2}$ is permitted at the ends of simply supported members. If the initial tensile stresses exceed the permissible values, bonded non-prestressed reinforcement must be provided to resist the total tensile force assuming an uncracked section.

- Final Service Stress: Section 18.3.3 defines three classes of prestressed flexural members, relative to the maximum allowable extreme fiber final tensile stress (f_t):

Uncracked	Class U	$f_t \leq 7.5(f'_c)^{½}$
Transition	Class T	$7.5(f'_c)^{½} < f_t \leq 12(f'_c)^{½}$
Cracked	Class C	$f_t > 12(f'_c)^{½}$

The permissible extreme fiber final compressive stress due to the post-tensioning plus the total service loads is limited to $0.60f'_c$. However, a permissible stress equal to $0.45f'_c$ has been added to the Coded for the condition of post-tensioned force plus sustained loads. It should be noted that the "sustained loads" mentioned in Section 18.4.2(a) include any portion of the live load that will be sustained for a sufficient period to cause significant time dependent deflections.

Concrete tensile stress limitations for Class U and T members at service loads apply to the "precompressed" tensile zone which is that portion of the member cross-section in which flexural tension occurs under dead and live loads.

Table 11 summarizes the applicable requirements for the above three classes of prestressed flexural members and, for comparison, for nonprestressed flexural members as well.

	Prestressed			Nonprestressed
	Class U	Class T	Class C	
Assumed behavior	Uncracked	Transition between uncracked and cracked	Cracked	Cracked
Section properties for stress calculation at service loads	Gross section 18.3.4	Gross section 18.3.4	Cracked section 18.3.4	No requirement
Allowable stress at transfer	18.4.1	18.4.1	18.4.1	No requirement
Allowable compressive stress based on uncracked section properties	18.4.2	18.4.2	No requirement	No requirement
Tensile stress at service loads 18.3.3	$\leq 7.5\sqrt{f'_c}$	$7.5\sqrt{f'_c} < f_t \leq 12\sqrt{f'_c}$	No requirement	No requirement
Deflection calculation basis	9.5.4.1 Gross section	9.5.4.2 Cracked section, bilinear	9.5.4.2 Cracked section, bilinear	9.5.2, 9.5.3 Effective moment of inertia
Crack control	No requirement	No requirement	10.6.4 Modified by 18.4.4.1	10.6.4
Computation of Δf_{ps} or f_s for crack control	—	—	Cracked section analysis	$M/(A_s$ x lever arm), or $0.6f_y$
Side skin reinforcement	No requirement	No requirement	10.6.7	10.6.7

TABLE 11

It should be noted that when calculating the services stresses the gross cross sectional area of the member must be included. This is because, as shown in Figure 12, the post-tensioning force expands beyond the allowable flexural cross sectional properties of the member the further you get away from the end anchorage zone. So for example, consider a T-beam in which the maximum flange width, bf, is limited by the Code for the calculation of flexural strength, however the width of the flange used to calculate A_g used in the P/A_g equation is equal to the midpoint of the slab span between each adjacent corresponding post-tensioned beams. It should be also noted that in the zone immediately adjacent to the anchorage point that is not precompressed, it is common to add conventional temperature/shrinkage reinforcement in the slab parallel to the span of the beam in assist in the control of cracking in the same affected area (see Item #3 above under Placement and Details).

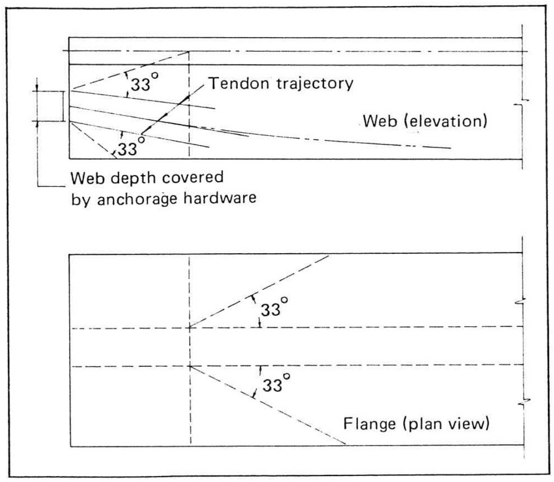


FIGURE 12

Finally, the Code also stipulates that a minimum average P/A_g final service stress of 125 psi should be provided for beams and slabs not exposed to corrosive environments. When unbonded tendons are used in a one-way slab for temperature and shrinkage control only, a minimum average P/A_g final service stress of only 100 psi needs to be provided (Section 7.12.3.1). However, the minimum average P/A_g final service stress for slabs and beams exposed to a corrosive environment is 150 and 200 psi, depending on the Durability Zone as defined by the PTI. The recommended maximum P/A_g is 300 psi.

Ultimate Flexural Strength:

The ultimate flexural strength of post-tensioned members can be calculated using the same assumptions as for nonprestressed members. Prestressing steel, however, does not have a well defined-yield point as does mild conventional reinforcement. As a post-tensioned cross-section reaches its flexural strength (as defined by a maximum compressive concrete strain of 0.003), stress in the prestressed reinforcement at nominal strength, f_{ps}, will vary depending on the amount of post-tensioning. The value of f_{ps} can be obtained using the conditions of equilibrium, stress-strain relations and strain compatibility, however, the analysis required is quite cumbersome, especially in the case of unbonded tendon. For bonded post-tensioning, the compatibility of strains can be considered at an individual section, while for unbonded tendon, compatibility relationships can be written only at the anchorage points and will depend on the entire cable profile and member loading.

To avoid such lengthy calculations, the code allows f_{ps} to be obtained by an approximate method using Equations 18-3, 18-4 and 18-5, where Equations 18-4 and 18-5 are intended for unbonded tendons and Equation 18-5 applies to members with high span to depth ratios (i.e.> 35) such as one-way and two-way slabs.

A more involved explanation of the ultimate strength design of post-tensioned members will be provided in Lecture 10, however, it should be noted that in almost all cases, the most economical design for ultimate flexural strength will utilize the maximum permissible tensile stresses for the concrete. In other words, the amount of tendons required to satisfy service stress conditions will typically be adequate for ultimate flexural strength.

Ultimate Shear Strength:

Shear in both statically determinate and continuous post-tensioned 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. However, it has been my personal experience to conservatively ignore this contribution of the post-tensioning effects. My rationale for this is as follows. First, the allowable shear contribution of the concrete, V_c, 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 a post-tensioned concrete member than conventionally reinforced beams because of the need to provide adequate means of supporting the tendon drape through out 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.