Cable-stayed bridge

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Cable-stayed bridge

The Rio-Antirrio bridge in Greece

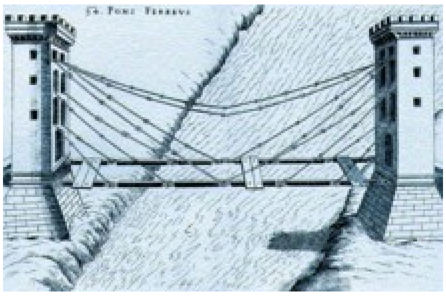
Ancestor	Suspension bridge
Related	None
Descendant	Side-spar cable-stayed bridge, Self-anchored suspension bridge, cantilever spar cable-stayed bridge
Carries	Pedestrians, bicycles, automobiles, trucks, light rail
Span range	Medium
Material	Steel rope, post-tensioned concrete box girders, steel or concrete pylons
Movable	No
Design effort	medium
Falsework required	Normally none

A **cable-stayed bridge** is a bridge that consists of one or more columns (normally referred to as *towers* or *pylons*), with cables supporting the bridge deck.

There are two major classes of cable-stayed bridges: In a *harp* design, the cables are made nearly parallel by attaching them to various points on the tower(s) so that the height of attachment of each cable on the tower is similar to the distance from the tower along the roadway to its lower attachment. In a *fan* design, the cables all connect to or pass over the top of the tower(s).

Compared to other bridge types, the cable-stayed is optimal for spans longer than typically seen in cantilever bridges, and shorter than those typically requiring a suspension bridge. This is the range in which cantilever spans would rapidly grow heavier if they were lengthened, and in which suspension cabling does not get more economical, were the span to be shortened.

History of development



Cable-stayed bridge by the Renaissance polymath Fausto Veranzio, from 1595/1616

Cable-stayed bridges can be dated back to 1595, where designs were found in a book by the Venetian inventor Fausto Veranzio, called *Machinae Novae*. Many early suspension bridges were of hybrid suspension and cable-stayed construction, including the 1817 footbridge Dryburgh Bridge, James Dredge's patented Victoria Bridge, Bath (1836), and the later Albert Bridge (1872) and Brooklyn Bridge (1883). Their designers found that the combination of technologies created a stiffer bridge, and John A. Roebling took particular advantage of this to limit deformations due to railway loads in the Niagara Falls Suspension Bridge.

The earliest known surviving example of a true cable-stayed bridge in the United States is E.E. Runyon's largely intact steel or iron bridge with wooden stringers and decking in Bluff Dale, Texas (1890), or his weeks-earlier but ruined Barton Creek Bridge between Huckabay, Texas and Gordon, Texas (1889 or 1890).[1][2] In the twentieth century, early examples of cable-stayed bridges included A. Gisclard's unusual Cassagnes bridge (1899), in which the horizontal part of the cable forces is balanced by a separate horizontal tie cable, preventing significant compression in the deck, and G. Leinekugel le Coq's bridge at Lézardrieux in Brittany (1924). Eduardo Torroja designed a cable-stayed aqueduct at Tempul in 1926.[3] Albert Caquot's 1952 concrete-decked cable-stayed bridge over the Donzère-Mondragon canal at Pierrelatte is one of the first of the modern type, but had little influence on later development.[3] The steel-decked Strömsund Bridge designed by Franz Dischinger (1955) is therefore more often cited as the first modern cable-stayed bridge.

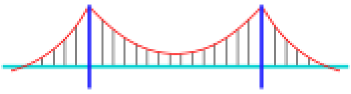
Other key pioneers included Fabrizio de Miranda, Riccardo Morandi and Fritz Leonhardt. Early bridges from this period used very few stay cables, as in the Theodor Heuss Bridge (1958). However, this involves substantial erection costs, and more modern structures tend to use many more cables to ensure greater economy.

Abdoun Bridge, **Amman**, **Jordan**

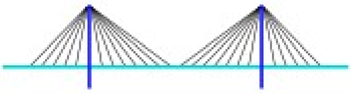
Comparison with suspension bridge

A multiple-tower cable-stayed bridge may appear similar to a suspension bridge, but in fact is very different in principle and in the method of construction. In the suspension bridge, a large cable hangs between two towers, and is fastened at each end to anchorages in the ground or to a massive structure. These cables form the primary load-bearing structure for the bridge deck. Before the deck is installed, the cables are under tension from only their own weight. Smaller cables or rods are then suspended from the main cable, and used to support the load of the bridge deck, which is lifted in sections and attached to the suspender cables. As this is done the tension in the cables increases, as it does with the live load of vehicles or persons crossing the bridge. The tension on the cables must be transferred to the earth by the anchorages, which are sometimes difficult to construct owing to poor soil conditions.

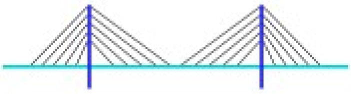
- Difference between types of bridges



Suspension bridge



Cable-stayed bridge, fan design



Cable-stayed bridge, harp design

Rama VIII Bridge, Thailand, a single tower asymmetrical type

In the cable-stayed bridge, the towers form the primary load-bearing structure. A cantilever approach is often used for support of the bridge deck near the towers, but areas further from them are supported by cables running directly to the towers. This has the disadvantage, compared to the suspension bridge, of the cables pulling to the sides as opposed to directly up, requiring the bridge deck to be stronger to resist the resulting horizontal compression loads; but has the advantage of not requiring firm anchorages to resist a horizontal pull of the cables, as in the suspension bridge. All static horizontal forces are balanced so that the supporting tower does not tend to tilt or slide, needing only to resist such forces from the live loads.

Key advantages of the cable-stayed form are as follows:

- much greater stiffness than the suspension bridge, so that deformations of the deck under live loads are reduced
- can be constructed by cantilevering out from the tower - the cables act both as temporary and permanent supports to the bridge deck
- for a symmetrical bridge (i.e. spans on either side of the tower are the same), the horizontal forces balance and large ground anchorages are not required

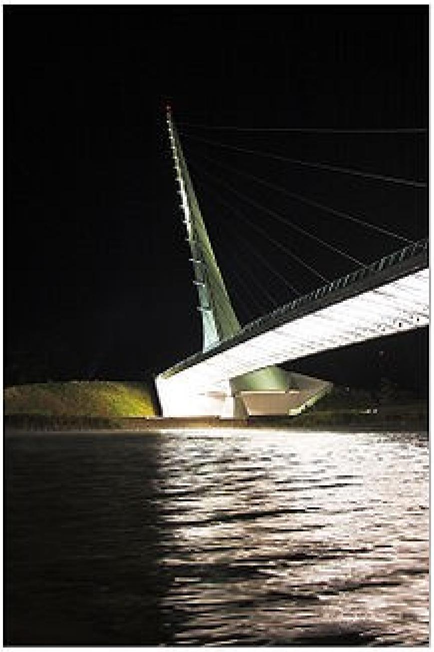
A further advantage of the cable-stayed bridge is that any number of towers may be used. This bridge form can be as easily built with a single tower, as with a pair of towers. However, a suspension bridge is usually built only with a pair of towers.

Variations

Side-spar cable-stayed bridge

Bandra–Worli Sea Link in Mumbai, India

Puente de la Unidad, joining San Pedro Garza García and Monterrey, a Cantilever spar cable-stayed bridge



Sundial Bridge at Turtle Bay in the United States

A side-spar cable-stayed bridge uses a central tower supported on only one side. This design could allow the construction of a curved bridge.

Cantilever-spar cable-stayed bridge

Far more radical in its structure, the Redding, California, Sundial Bridge is a pedestrian bridge that uses a single cantilever spar on one side of the span, with cables on one side only to support the bridge deck. Unlike the other cable-stayed types shown this bridge exerts considerable overturning force upon its foundation and the spar must resist the bending caused by the cables, as the cable forces are not balanced by opposing cables. The spar of this particular bridge forms the gnomon of a large garden sundial. Related bridges by the architect

Santiago Calatrava include the Puente del Alamillo (1992), Puente de la Mujer (2001), and Chords Bridge (2008).

Multiple-span cable-stayed bridge

Cable-stayed bridges with more than three spans involve significantly more challenging designs than do 2-span or 3-span structures.

In a 2-span or 3-span cable-stayed bridge, the loads from the main spans are normally anchored back near the end abutments by stays in the end spans. For more spans, this is not the case and the bridge structure is less stiff overall. This can create difficulties both in the design of the deck and the pylons. Examples of multiple-span structures in which this is the case include Ting Kau Bridge, where additional 'cross-bracing' stays are used to stabilise the pylons; Millau Viaduct and Mezcala Bridge, where twin-legged towers are used; and General Rafael Urdaneta Bridge, where very stiff multi-legged frame towers were adopted. A similar situation with a suspension bridge is found at both the Great Seto Bridge and San Francisco – Oakland Bay Bridge where additional anchorage piers are required after every set of three suspension spans - this solution can also be adapted for cable-stayed bridges.[4]

Extradosed bridge

Octavio Frias de Oliveira bridge, in São Paulo, Brazil. It is the only bridge in the world that has two curved tracks supported by a single concrete mast.

The extradosed bridge is a cable-stayed bridge but with a more substantial bridge deck that, being stiffer and stronger, allows the cables to be omitted close to the tower and for the towers to be lower in proportion to the span.

Cable-stayed cradle-system bridge

Cable-Bridge over Krishnarajapuram Railway station

A cradle system carries the strands within the stays from bridge deck to bridge deck, as a continuous element, eliminating anchorages in the pylons. Each epoxy-coated steel strand is carried inside the cradle in a one-inch (2.54 cm) steel tube. Each strand acts independently, allowing for removal, inspection and replacement of individual strands. The first two such bridges are the Penobscot Narrows Bridge, completed in 2006, and the Veterans' Glass City Skyway, completed in 2007.[5]

Related bridge types

Self anchored suspension bridge

Proposed eastern span replacement of the San Francisco – Oakland Bay Bridge in the USA - a self-anchored suspension span

Post-Tensioning Tendon Installation and Grouting Manual

Chapter 1 - Introduction

1.1 Objective

One of the major advancements in bridge construction in the United States in the second half of the twentieth century was the development and use of prestressed concrete. Prestressed concrete bridges, offer a broad range of engineering solutions and a variety of aesthetic opportunities. The objective of this Manual is to provide guidance to individuals involved in the installation or inspection of post-tensioning work for post tensioned concrete bridges including post-tensioning systems, materials, installation and grouting of tendons.

1.1.1 Benefits of Post-Tensioning

The tensile strength of concrete is only about 10% of its compressive strength. As a result, plain concrete members are likely to crack when loaded. In order to resist tensile stresses which plain concrete cannot resist, it can be reinforced with steel reinforcing bars. Reinforcing is selected assuming that the tensile zone of the concrete carries no load and that tensile stresses are resisted only by tensile forces in the reinforcing bars. The resulting reinforced concrete member may crack, but it can effectively carry the design loads (Figure 1.1).

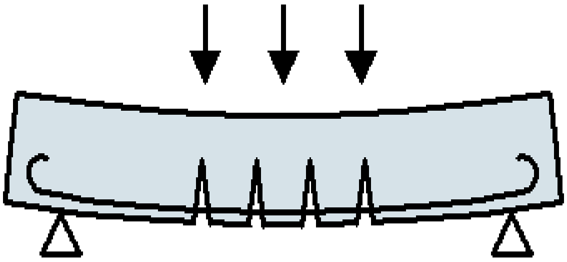


Figure 1.1 - Reinforced concrete beam under load

Although cracks occur in reinforced concrete, the cracks are normally very small and uniformly distributed. However, cracks in reinforced concrete can reduce long-term durability. Introducing a means of precompressing the tensile zones of concrete members to offset anticipated tensile stresses reduces or eliminates cracking to produce more durable concrete bridges.

1.1.2 Principle of Prestressing

The function of prestressing is to place the concrete structure under compression in those regions where load causes tensile stress. Tension caused by the load will first have to cancel the compression induced by the prestressing before it can crack the concrete. Figure 1.2 (a) shows a plainly reinforced concrete simple-span beam and fixed cantilever beam cracked under applied load. Figure 1.2(b) shows the same unloaded beams with prestressing forces applied by stressing high strength tendons. By placing the prestressing low in the simple-span beam and high in the cantilever beam, compression is induced in the tension zones; creating upward camber.

Figure 1.2(c) shows the two prestressed beams after loads have been applied. The loads cause both the simple-span beam and cantilever beam to deflect down, creating tensile stresses in the bottom of the simple-span beam and top of the cantilever beam. The Bridge Designer balances the effects of load and prestressing in such a way that tension from the loading is compensated by compression induced by the prestressing. Tension is eliminated under the combination of the two and tension cracks are prevented. Also, construction materials (concrete and steel) are used more efficiently; optimizing materials, construction effort and cost.

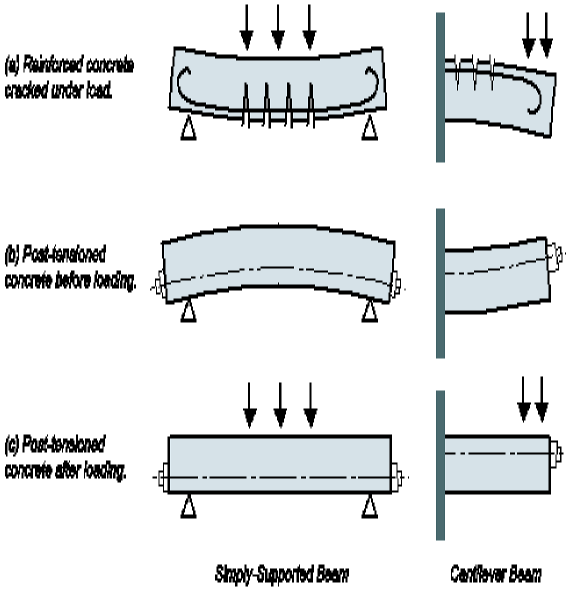


Figure 1.2 - Comparison of Reinforced and Prestressed Concrete Beams

Prestressing can be applied to concrete members in two ways, by pretensioning or post-tensioning. In pretensioned members the prestressing strands are tensioned against restraining bulkheads before the concrete is cast. After the concrete has been placed, allowed to harden and attain sufficient strength, the strands are released and their force is transferred to the concrete member. Prestressing by post-tensioning involves installing and stressing prestressing strand or bar tendons only after the concrete has been placed, hardened and attained a minimum compressive strength for that transfer.

1.1.3 Post-Tensioning Operation

Compressive forces are induced in a concrete structure by tensioning steel tendons of strands or bars placed in ducts embedded in the concrete. The tendons are installed after the concrete has been placed and sufficiently cured to a prescribed initial compressive strength. A hydraulic jack is attached to one or both ends of the tendon and pressurized to a predetermined value while bearing against the end of the concrete beam. This induces a predetermined force in the tendon and the tendon elongates elastically under this force. After jacking to the full, required force, the force in the tendon is transferred from the jack to the end anchorage.

Tendons made up of strands are secured by steel wedges that grip each strand and seat firmly in a wedge plate. The wedge plate itself carries all the strands and bears on a steel anchorage. The anchorage may be a simple steel bearing plate or may be a special casting with two or three concentric bearing surfaces that transfer the tendon force to the concrete. Bar tendons are usually threaded and anchor by means of spherical nuts that bear against a square or rectangular bearing plate cast into the concrete. For an explanation of post-tensioning terminology and acronyms, see Appendix A.

After stressing, protruding strands or bars of permanent tendons are cut off using an abrasive disc saw. Flame cutting should not be used as it negatively affects the characteristics of the prestressing steel. Approximately 20mm (¾ in) of strand is left to protrude from wedges or a certain minimum bar length is left beyond the nut of a bar anchor. Tendons are then grouted using a cementitious based grout. This grout is pumped through a grout inlet into the duct by means of a grout pump. Grouting is done carefully under controlled conditions using grout outlets to ensure that the duct anchorage and grout caps are completely filled. For final protection, after grouting, an anchorage may be covered by a cap of high quality grout contained in a permanent non-metallic and/or concrete pour-back with a durable seal-coat.

Post-tensioning and grouting operations require certain levels of experience, as outlined in Appendix B.

1.1.4 Post-Tensioning Systems

Many proprietary post-tensioning systems are available. Several suppliers produce systems for tendons made of wires, strands or bars. The most common systems found in bridge construction are multiple strand systems for permanent post-tensioning tendons and bar systems for both temporary and permanent situations. Refer to manufacturers' and suppliers' literature for details of available systems. Key features of three common systems (multiple-strand and bar tendons) are illustrated in Figures 1.3, 1.4 and 1.5.

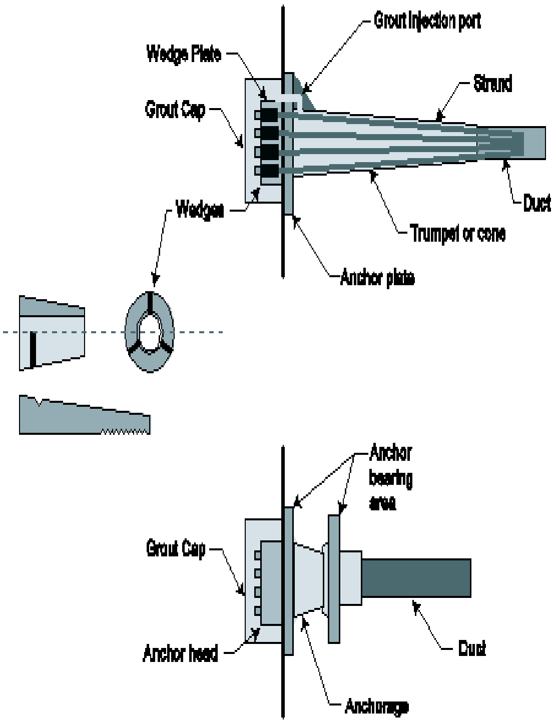


Figure 1.3 - Typical Post-Tensioning Anchorage Hardware for Strand Tendons

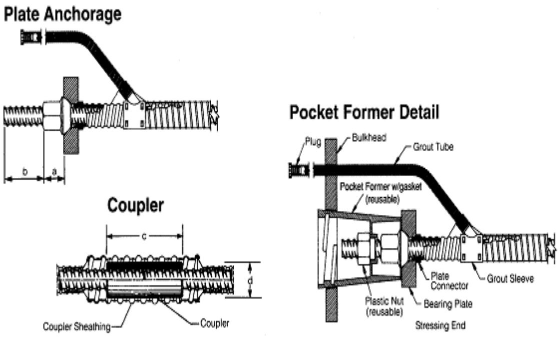


Figure 1.4 - Typical Post-Tensioning Bar System Hardware. (Courtesy of Dywidag Systems International)

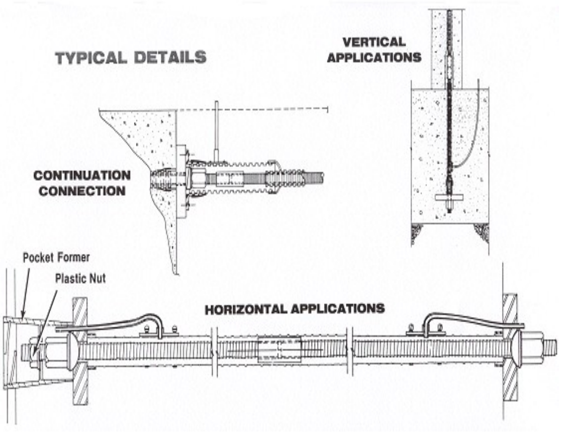


Figure 1.5 - Typical Post-Tensioning Bar System Hardware. (Courtesy of Williams Form Engineering Corporation)

1.2 Permanent Post-Tensioned Applications

1.2.1 Cast-in-Place Bridges on Falsework

Bridges of this type have a superstructure cross-section of solid or cellular construction.

They are built on-site using formwork supported by temporary falsework (Figure 1.6). Formwork creates the shape of the concrete section and any internal voids or diaphragms. Reinforcement and post-tensioning ducts are installed in the forms and then the concrete is placed, consolidated and cured. When the concrete attains sufficient strength, post-tensioning is installed and stressed to predetermined forces.

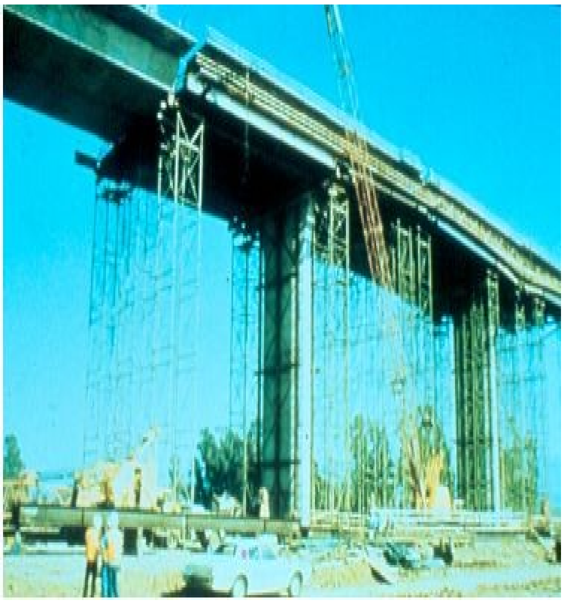


Figure 1.6 - Cast -In-Place Post-
Tensioned Construction in California

Longitudinal post-tensioning typically comprises multi-strand tendons smoothly draped to a designed profile. In continuous spans, the tendon profile lies in the bottom of the section in the mid-span region and rises to the top of the section over interior supports. In simple spans and at the expansion ends of continuous spans, post-tensioning anchors are arranged vertically so that the resultant of the tendon anchor force passes close to the centroid of the section. A draped profile of this type provides the most effective distribution of internal prestress for this type of construction.

1.2.2 Post-Tensioned AASHTO, Bulb-T, and Spliced Girders

Precast, post-tensioned AASHTO and bulb-T girders are usually pre-tensioned sufficiently at the precast plant to carry their own self weight for transportation to the site and erection. On site, girders are first erected as simple spans. However, over the interior piers of a three or four-span unit, they are made continuous by cast-in-place joints that connect the girder ends and form transverse, reinforced diaphragms.

Post tensioning ducts cast into the webs are spliced through the cast-in-place joints. The ducts follow a smoothly curved, draped profile along each girder line, rising to the top of the girders over the interior piers and draping to the bottom flange in mid-span regions. Before the deck slab is cast, some or all of the tendons running the full length of the multi-span unit are installed and stressed, making each simple span I-girder into a series of continuous spans. When the deck slab has been cast and cured, additional tendons may be installed and stressed on the fully composite section. Tendons may be anchored in a variety of configurations at the ends of each continuous unit.

Longer spans can be built using similar techniques. A variable depth girder section cantilevering over a pier can be spliced to a typical precast girder in the main and side-spans. An example is shown in Figure 1.7

Figure 1.7-Spliced Haunched I-Girder of Main

Temporary supports are needed at the splice location in the side spans. The ends of girders have protruding mild reinforcing to help secure the girder to the closure concrete and ducts that splice with those of other girder components to accommodate tendons over the full length of the main unit. The variable depth girder sections are placed over the piers, aligned with the girders of the side spans, and closures cast. Usually, temporary strong-back beams support the drop-in girder of the main span while closures are cast.

The sequence for erecting and temporarily supporting this type of I-girder construction is illustrated in Figure 1.8. After all closures have been cast and have attained the necessary strength, longitudinal post-tensioning tendons are installed and stressed. To maximize the efficiency of the post-tensioning, phased stressing is necessary. Some of the longitudinal tendons are stressed on the I-girder section alone (i.e. while it is non-composite). The remaining tendons are stressed after the deck slab has been cast and act upon the full composite section.

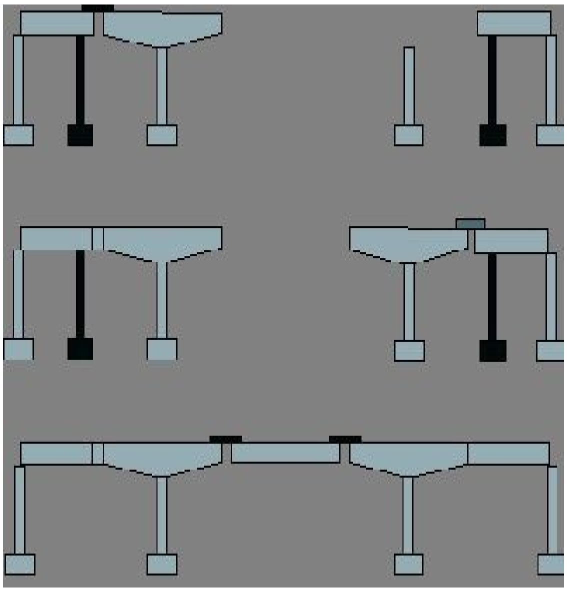


Figure 1.8 - Erection Sequence and Temporary Supports for Spliced I-Girder

1.2.3 Cast-in-Place Segmental Balanced Cantilever Bridges

An example of cast-in-place balanced cantilever construction using form travelers is shown in Figure 1.9. Form travelers support the concrete until it has reached a satisfactory strength for post-tensioning. Longitudinal post-tensioning comprises cantilever tendons in the top slab at supports and continuity tendons in both top and bottom slabs through the mid-span regions.

Figure 1.9 - Cast-In-Place Segmental construction using Form Travelers

Cast-in-place balanced cantilever construction was adopted for four bridges on the Foothills Parkway in Tennessee designed by the Eastern Federal Lands Division of the Federal Highway Administration (Figure 1.10).

1.2.4 Precast Segmental Balanced Cantilever Bridges

Precast segmental balanced cantilever construction involves the symmetrical erection of segments about a supporting pier. When a segment is lifted into position, adjoining match-cast faces are coated with epoxy and temporary post-tensioning bars are installed and stressed to attach the segment to the cantilever. Typically, after a new, balancing segment, is in place on each end of the cantilever, post-tensioning tendons are installed and stressed from one segment on one end of the cantilever to its counter-part on the other. Consequently, as segments are added, more top cantilever tendons are added.

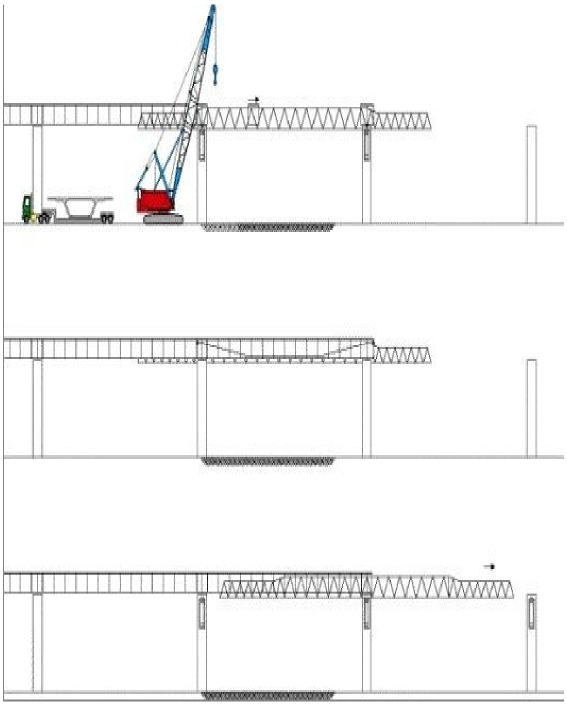


Figure 1.11 - Precast Segmental
Balanced Cantilever Construction.

Figure 1.11 shows two typical methods of placing precast segments in balanced cantilever; using cranes with stability towers at each pier and using an overhead launching gantry. When all segments of a new cantilever have been erected and tendons stressed, a closure joint is made at mid-span. Continuity post-tensioning tendons are installed and stressed through the closure to make the cantilevers continuous.

1.2.4.1 Typical Features of Precast Cantilever Segments

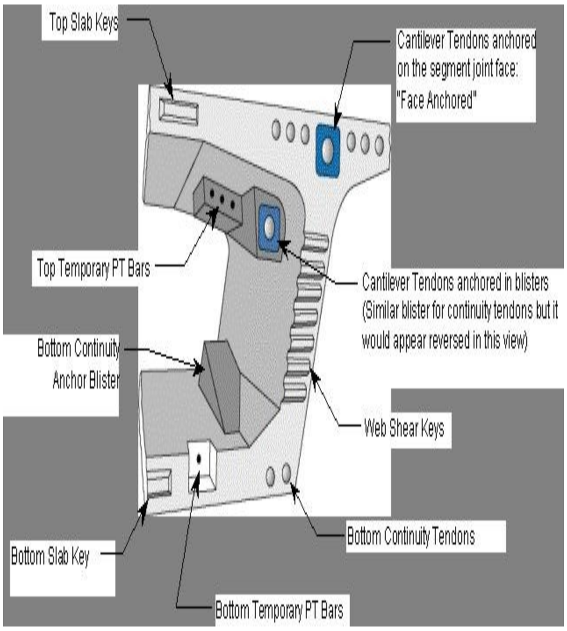


Figure 1.12 - Typical Balanced
Cantilever Segment

Figure 1.12 offers a perspective showing various features of a typical precast cantilever segment, tendon locations and anchors. These are briefly as follows.

1.2.4.2 Cantilever tendons

Longitudinal post-tensioning tendons for cantilever construction are contained within the top slab, usually spaced in a single layer over each web. For long spans, a second layer of tendons in the thickened haunch of the top slab may be required. The layout pattern of the ducts is always the same at each match-cast joint and ducts shift sideways or up and down within a segment to make up the full tendon profile from an anchor at one end of the cantilever to that at the other. Tendons terminate at anchors by a shift of the duct from its row in the slab to an anchorage. Relative to each segment, cantilever tendons always anchor in the same location. This may be in the end face of the segment or within an anchor block (or "blister") on the interior of the segment.

1.2.4.3 Continuity Tendons

To complete a span, the ends of two adjacent cantilevers are connected by a cast-in-place closure at or near mid-span of interior spans. In end spans, the closure joint is usually nearer to the end expansion joint. When the closure concrete attains sufficient strength, longitudinal post-tensioning (continuity) tendons are installed, tensioned and grouted. Figure 1.13 depicts typical locations and layouts for bottom continuity tendons at mid-span.

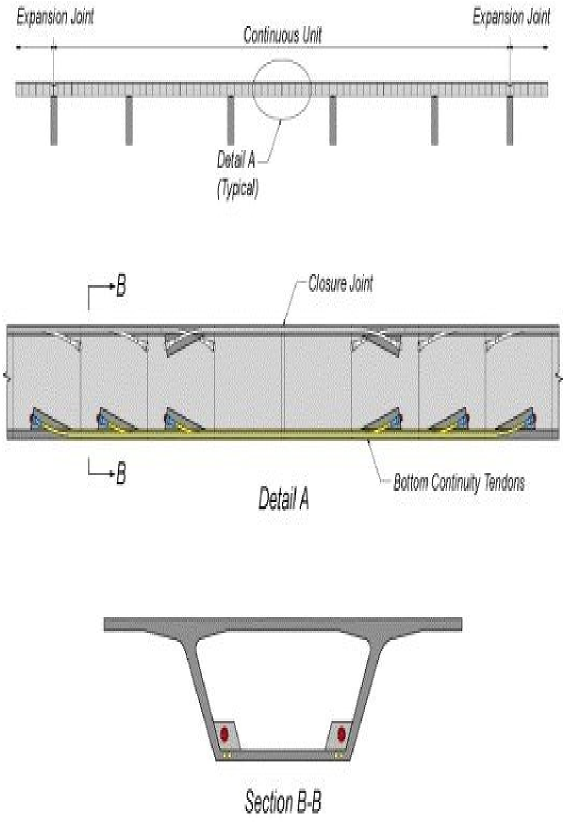


Figure 1.13 - Bottom Continuity Tendons for Balanced Cantilever Construction

1.2.5 Precast Segmental Span-by-Span Bridges

Span-by-span construction involves the erection of all segments of a span on a temporary support system with small closure joints cast at one or both ends next to the segments over the pier. Figure 1.14 shows typical phases for span-by-span construction.

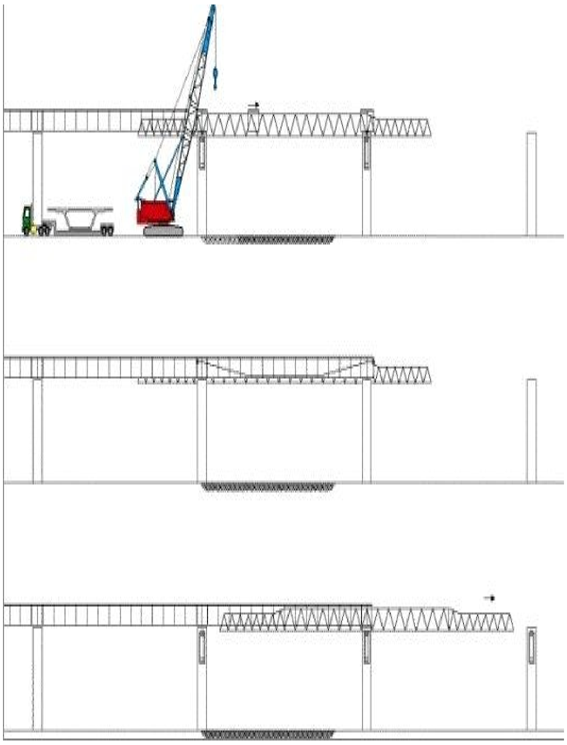


Figure 1.14 - Span-By-Span Construction

Tendons, usually external, are installed and stressed from the pier segment at one end of the span to that at the other (Figure 1.15). The tendons drape between the piers, being anchored near the top of the section over the piers but deviated to the bottom of the section within the mid-span region.

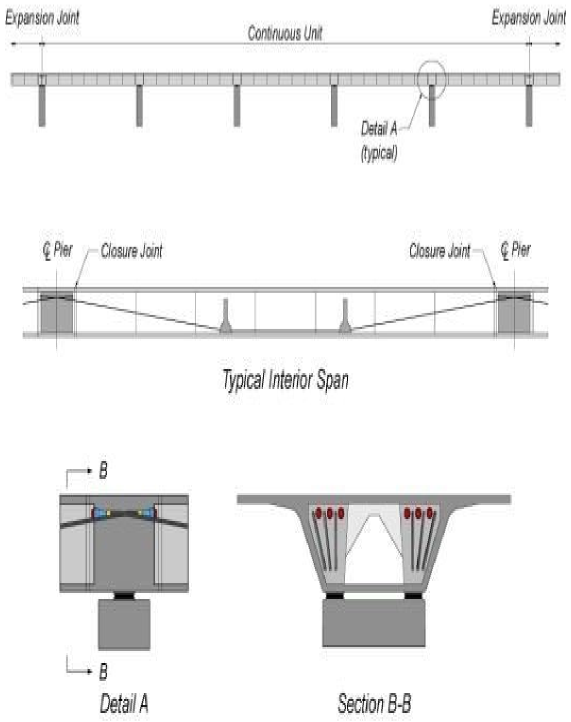


Figure 1.15 - Interior Span Post -Tensioning for Span-By-Span Construction.

In order to achieve continuity with the next span, the tendons from one span overlap with the tendons of the next in the top of the pier segment. At the very ends of each continuous unit, the ends of the tendons anchor in the diaphragm of the expansion joint segment with anchors dispersed vertically and approximately parallel to the web of the box.

1.2.6 Transverse Post-Tensioning of Superstructures

For bridge decks, transverse post-tensioning is used in cast-in-place solid slabs and to transversely connect spans made of precast-prestressed slabs placed side-by-side by means of narrow cast-in-place longitudinal joints. Transverse post-tensioning is frequently used in deck slabs of cast-in-place or precast boxes, diaphragms, transverse ribs and similar applications. For further information and examples, see Appendix C.

1.2.7 Post-Tensioning of Substructures

Substructures for standard AASHTO I-girders, Bulb-T's, spliced girders, cast-in-place post-tensioned and many segmental structures are typically built using reinforced concrete construction. However, for large bridges or to accommodate other special construction needs, post-tensioned substructures may be appropriate. Post-tensioned substructures may be used for bridges of all types of superstructures. Some of the more typical applications are shown in the following sections.

1.2.7.1 Hammerhead Piers

Transverse post-tensioned tendons using strand or bar tensile elements provide an effective reinforcing scheme for Hammerhead Piers (Figure 1.16). This is especially true for large hammerheads with significant cantilevers or where vertical clearances restrict the available depth. The tendons are internal to the concrete and are stressed and grouted after the pier concrete has reached sufficient strength.

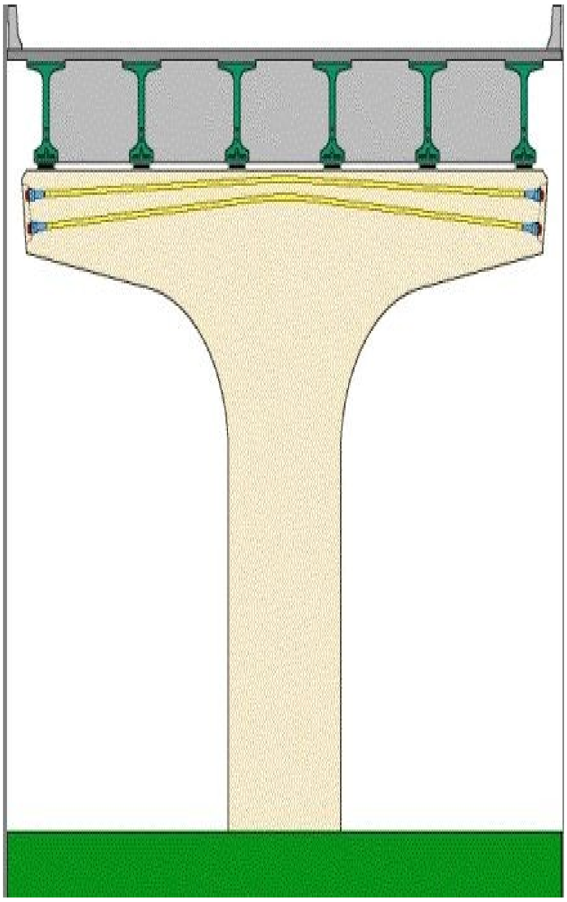


Figure 1.16 - Post-Tensioning in Hammerhead Piers

1.2.7.2 Straddle Bents

Straddle bents are often required to support upper level roadways in complex multi-level interchanges (Figure 1.17). Limited vertical clearances often restrict the depths of the straddle bent caps, resulting in a post-tensioned rather than conventionally reinforced concrete member.

In a typical straddle bent, tendons drape to a prescribed profile that may be similar to the drape in a beam on simple supports, or it may rise over the columns where a monolithic connection is made to transfer moments into the columns and provide frame action. The columns may be reinforced or post-tensioned, depending upon the magnitude of the forces and moments induced in the frame.

Tendons in straddle bents are internal and grouted during construction. However, it is possible to apply external tendons of a similar type to repair, or rehabilitate a damaged structure.

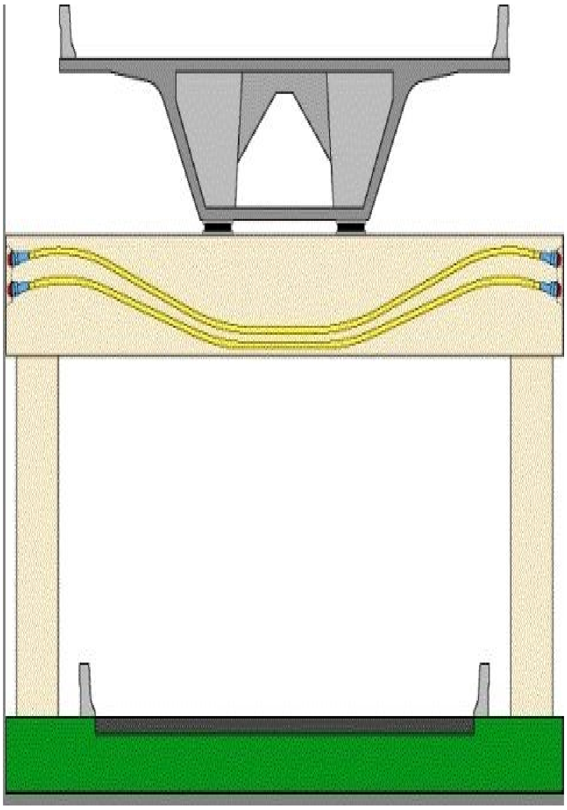


Figure 1.17 - Post-Tensioning in Straddle Bents

1.2.7.3 Cantilever Piers

Cantilever piers (C-piers) are often used in multi-level interchanges or in flyover bridges where a concentric column would intrude into a horizontal clearance associated with an underlying roadway. For structural efficiency and economy, a typical cantilever pier usually contains transverse and vertical post-tensioning (Figure 1.18) rather than solely being reinforced.

Detailing of cantilever piers should provide for proper development of prestressing forces in the cantilever, column and footing. Anchors at corners must cross in an effective manner to oppose tension and develop pre-compression all around the exterior of the pier. An alternative would be to use a continuous tendon rather than two separate tendons.

Tendons are internal, stressed and grouted during construction. Similar external tendons may be used for repair or rehabilitation. Special attention would be needed, however, to anchor them and develop forces around the top corner and into the footing.

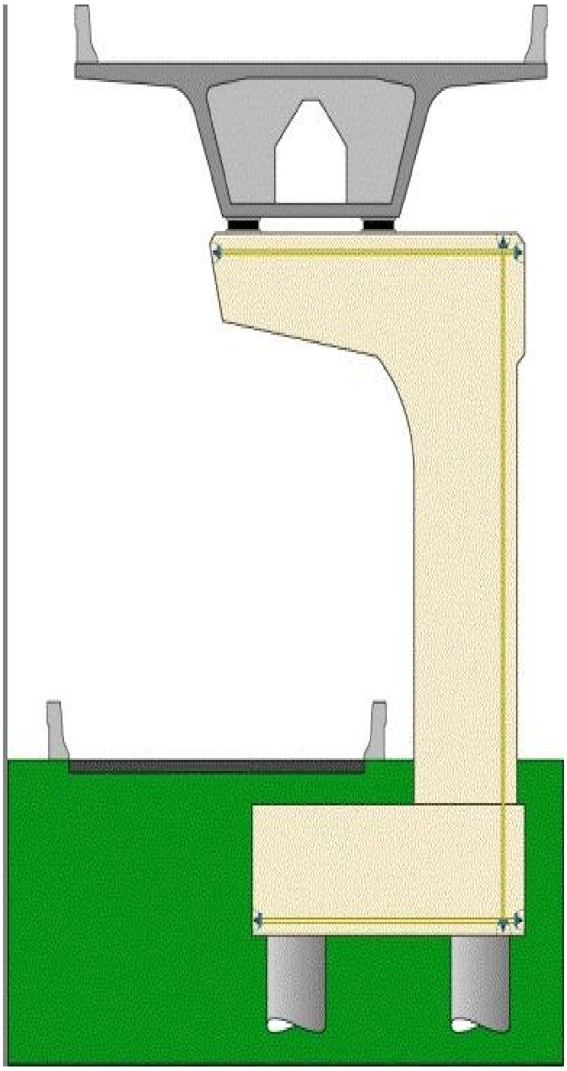


Figure 1.18 - Post-Tensioning in Cantilever Piers.

1.2.7.4 Precast Piers

Hollow section, precast concrete segmental piers have been used on several projects. Vertical post-tensioning usually consists of PT bars for short to moderate heights, up to about 12M (40 feet). Strand tendons are usually needed for taller piers. Bars are typically anchored in footings and extend to the pier caps. Strand tendons are usually continuous and extend from an anchor in the cap on one side of the pier, down the pier, loop through the footing and up the opposite side to another anchor in the cap. Post-tensioning bars are also used to temporarily secure precast segments and compress epoxy in the joints as they are erected prior to installing permanent strand tendons. Hollow precast, oval section segments with an aesthetically shaped octagonal exterior with concave faces, were used for the Linn Cove Viaduct on the Blue Ridge Parkway in North Carolina (Figure 1.19).

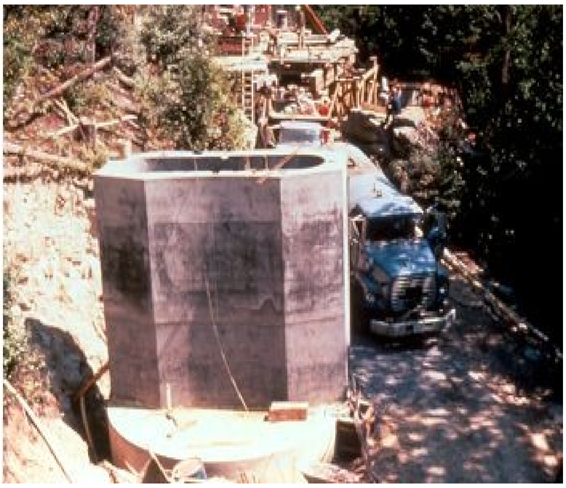


Figure 1.19 - Precast Hollow Segmental Piers, Linn Cove Viaduct, North Carolina

Precast segmental piers with an I-section were used for the Mid-Bay Bridge in Florida. The taller piers were post-tensioned with strand tendons, looping through the foundations, (Figure 1.20).

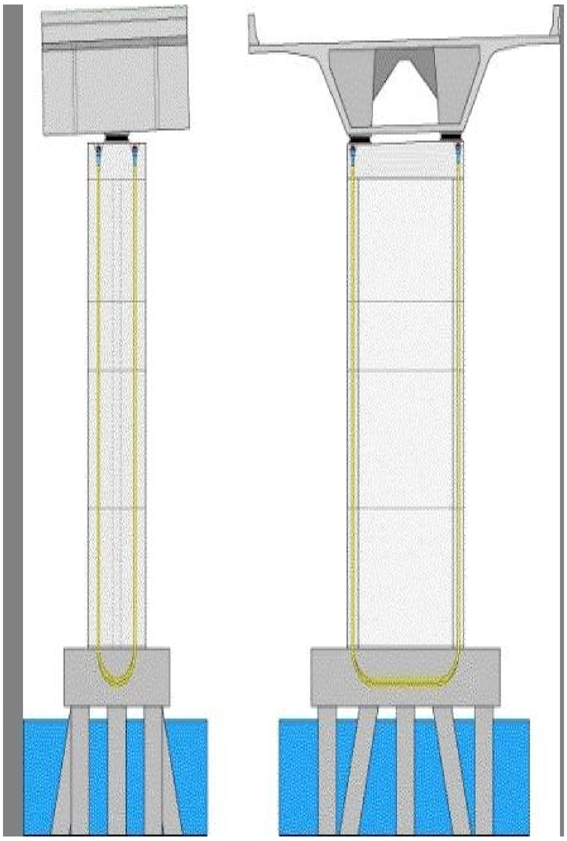


Figure 1.20 - Precast I-Piers.

1.2.7.5 Precast Segmental Box Section Arches

Precast concrete hollow box section segments were used for the main arch ribs of the Natchez Trace Parkway Bridge in Tennessee (Figure 1.21). These were erected using temporary cable stays to the central pier column, which in turn were balanced by tie-backs anchoring in the adjacent hillsides. Temporary post-tensioning bars were used to secure each new segment to that previously erected to compress the epoxy joint.

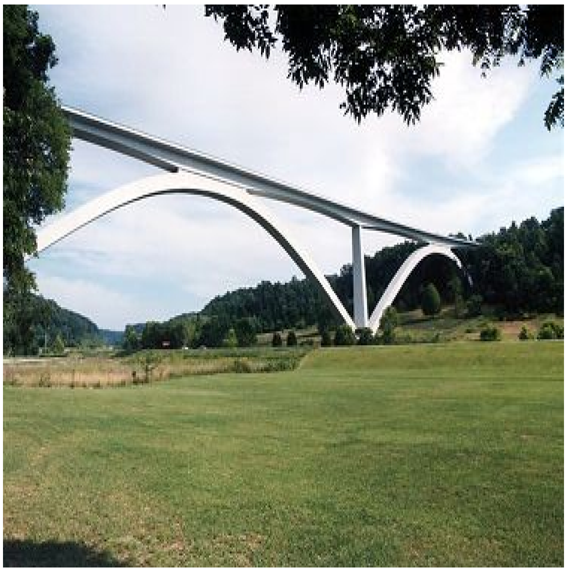


Figure 1.21 - Natchez Trace Parkway Arches, Tennessee.

1.2.7.6 Transverse, Confinement Tendons at Tops of Piers

Large concentrated bearing loads on the top of piers induce local transverse tensile stresses. These stresses may be resisted by mild steel reinforcement or by transverse post-tensioning. Because tendon lengths are typically short, bar tendons are typically used in this application. Special conditions may call for the use of strand tendons. An example of this is the transverse post-tensioning tendons in the tops of the large elliptical piers of the main span unit of Sunshine Skyway Bridge in Florida. Internal multi-strand transverse tendons were used in a hoop layout to provide the required transverse prestressing.

1.3 Temporary Longitudinal Post-Tensioning (Bars) - Typical Applications

1.3.1 Erection of Precast Cantilever Segments

Temporary post-tensioning bars are a key feature of precast cantilever erection. In cantilever erection, each new precast segment added to the cantilever is first secured to the previous segment using temporary post-tensioning bars to squeeze the epoxy joint and hold the segment until the main cantilever tendons can be installed. Construction operations are arranged to make it possible to lift a segment, apply epoxy, install temporary bars and squeeze the joint before the epoxy begins to set.

Depending on the size of the segment, there may be four to eight temporary bars distributed around the cross section. In most precast cantilever bridges, there is at least one temporary PT bar in a duct in the concrete wing of the segment. In some bridges, temporary PT bars anchor in blocks on the underside of the top slab and on the top of the bottom slab. Alternatively, bars may be installed in ducts within the top and bottom slabs and anchored in blockouts at the segment joints (Fig. 1.22)

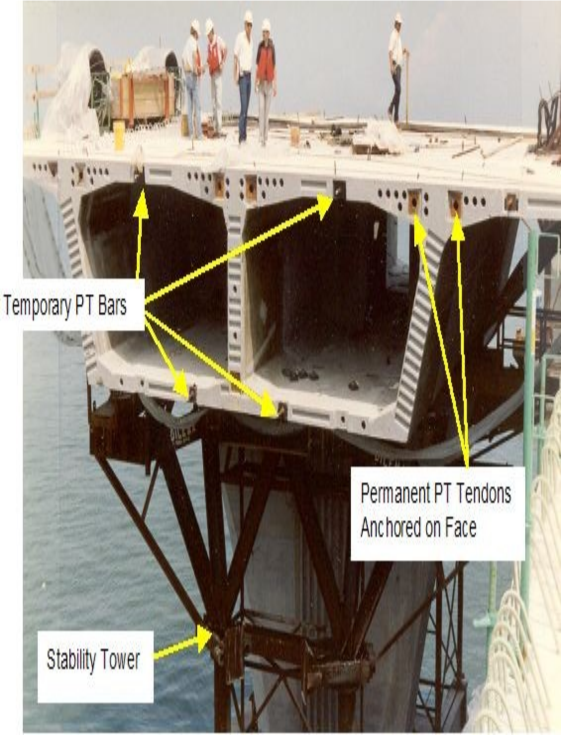


Figure 1.22 - Temporary PT Bars for Segment Erection

1.3.2 Closure of Epoxy Joints in Span-by-Span Erection

Temporary PT bars are usually needed for span-by-span erection in order to squeeze the epoxy. In such cases, the bars may be anchored at temporary blocks (blisters) on the interior of the section or at diaphragms and deviators, passing through them in ducts. Using slow-set epoxy, it is possible to erect and epoxy several segments of a span at one time.

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Post-Tensioning Tendon Installation and Grouting Manual

Chapter 3 - Post-Tensioning Duct and Tendon Installation

This Chapter basically addresses construction procedures and operations from Shop Drawings, through tendon installation and stressing. Grouting is addressed in the next chapter. Information and details in these two Chapters may be used for guidance.

3.1 Shop Drawings

3.1.1 Drawings and Details

3.1.1.1 Purpose

To permit completion and to encourage further development in the field of post-tensioned bridge construction, in general, normal contract plans and specifications do not specify a particular manufacturer's post-tensioning system. The Engineer of Record usually selects the type, size, location and number of tendons, but the Contractor selects the anchorage system. All post-tensioning systems should have prior approval before being used.

All systems now in general use have been developed by independent companies and represent different methods by which the prestressing force is applied. Each offers certain advantages as compared to the others, but each will, when properly installed and stressed, accomplish the intended result.

A post-tensioning system proposed by a Contractor should be shown on shop drawings. These drawings should include details for the methods and materials used, including any rearrangement of or addition to reinforcing steel that differs from that shown on the contract plans. Shop drawings represent an important supplement to Contract Plans.

Shop drawings are normally reviewed by the Bridge Designer. The Designer normally checks them for completeness, contract compliance, clearances or interference of ducts and reinforcing steel. Despite the approval process, the Contractor remains responsible for the correctness of the shop drawings and ensuing construction.

Shop drawings are needed for integration of approved post-tensioning systems (i.e. post-tensioning supplier's information and details), reinforcement, post-tensioning, and other embedded items (including those for the Contractor's chosen "means and methods" of construction) for precast and cast-in-place components.

3.1.1.2 Typical Contents

Shop drawings from a Manufacturer of a Post-tensioning system typically address various details such as:

- Dimensions, details and materials for all manufactured components.
- For strand systems, dimensions and details of anchors, wedge-plates, wedges, for each size and tendon.
- For bar systems, dimensions and details of anchor plates, anchor nuts, bars and couplers for each bar size.
- Details of grout inlets and outlets at anchorages.
- Size, type connection and sealing details of grout caps.
- For each type of duct, dimensions, details, type of material, duct connectors and methods of connecting ducts to anchor cones (trumpets).
- Details of means and methods of attaching intermediate grout inlets and outlets to the ducts, including sizes of grout pipes, materials, and shut-off valves.
- Dimensions, clearances, force and stroke of stressing jacks for post-tensioning bars and strands, including single, mono-strand and multi-strand jacks as necessary.
- Typical details of ancillary equipment such as power source, hydraulic lines, pressure gages for use with the stressing jacks.
- Jack calibration charts to show relationship between dial gage pressure and force delivered.

Often, much of the above information is available from a catalogue data, particularly for anchors, couplers, wedges, nuts, bars, ducts, jacks and equipment. Other information shown on additional shop drawings prepared by a Contractor or his (Specialty) Engineer or in a post-tensioning or construction manual for a specific project usually includes procedures, such as:

- Duct profile and minimum clearances.
- Details, types and locations of duct supports, connections to temporary bulkheads, and means of maintaining alignment and profile.
- The method for installing strands, individually or in a complete bundle for each tendon.
- The sequence in which tendons are stressed.
- The end(s) from which tendons are stressed.
- Assumed coefficient of friction (m) and wobble coefficient (k).
- The estimated elongation and maximum jacking force for each tendon.
- The estimated wedge set or seating loss.

- Similar information for post-tensioning bar tendons.
- When temporary post-tensioning bars are used to secure a precast match cast segment, the sequence and force to which each should be coupled and stressed around the cross-section.
- The sequence and means by which temporary post-tensioning bar or strand tendons are de-tensioned and removed.
- For all permanent installations, locations of grout inlets and outlets, details, direction of grouting and sequence in which tendons are grouted (See also Chapter 4).

3.1.1.3 Typical Approval Process

Typical responsibilities associated with shop drawings include:

- Contractor: Arrange for the preparation of the necessary shop drawings and other relevant information required by the Contract, see that shop drawings are submitted to the Engineer (usually the Designer) for review and approval, receive review comments, make revisions as necessary and carry out construction accordingly.
- Contractor's Engineer: the person or firm who prepares calculations and shop drawings on behalf of the Contractor.
- Engineer (Designer): Receive, log and review all submittals for compliance with the information conveyed on the plans and provide approval, reject, seek amendment or clarification as necessary. The Engineer may be a member of a state (Owner) agency or private firm engaged by that State or Owner.
- CEI - Construction Engineering and Inspection: This is the person, firm or agency representing the interest of the State or Owner on the job-site (Resident Engineer).

A typical shop drawing submittal, review and approval process for a Design-Bid-Build project is illustrated in Figure 3.1. This would be different for a Design-Build project.

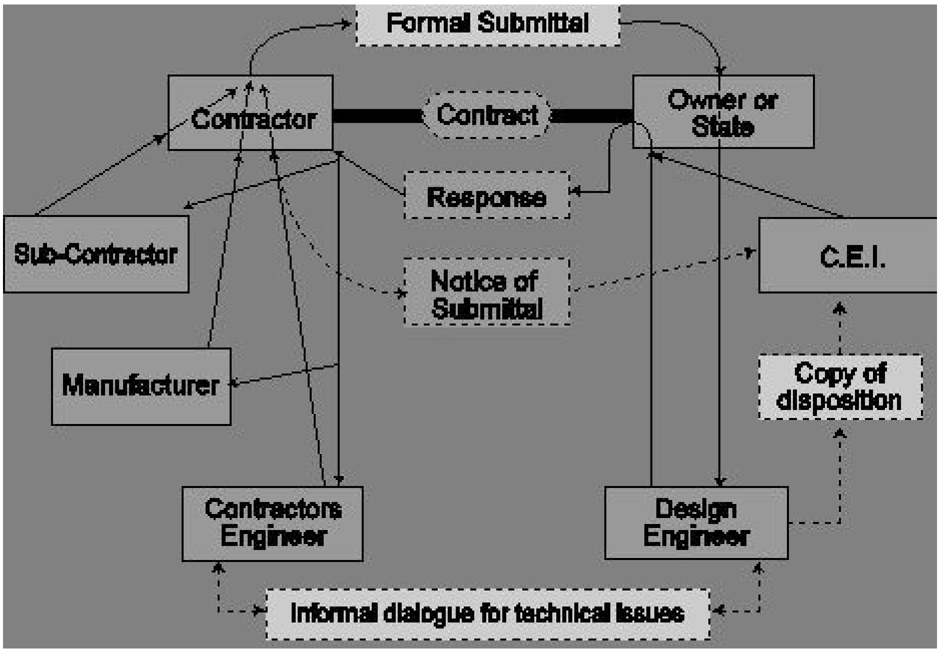


Figure 3.1 - Typical Shop Drawing Approval Process for Post-tensioning

3.1.2 Stressing Calculations

To ensure that the correct force is applied to each tendon, calculations are made to account for losses (friction, wobble, wedge-set and anchor friction) along the length of a tendon and to estimate the elongation as a check against the gauge pressure on the jack. Calculations are usually made by the Contractors Engineer or installer of the Post-Tensioning and should be checked by the Engineer (Designer or CEI). Key information, such as jacking force or gauge pressure and anticipated elongation, is extracted for stressing.

Stressing of a tendon may be performed from one or both ends. Stressing from both ends may be sequential, first from one end then the other, or simultaneous using two jacks. In some types of construction, it may only be necessary to stress from one end; for example, where tendons are relatively short, say up to about 50M (150 feet) and have relatively small friction loss. However, for long tendons, especially those within internal ducts set to a curved profile that passes continuously through three or four I-girder spans, friction loss may be so significant that it is essential to stress the tendon from both ends to ensure adequate force throughout.

Wedge-set should be taken into account for both the stressing end and dead end of a tendon. For long tendons, often the elongation may be greater than the travel on the jack. It is then necessary to take more than one pull of the jack. Each time the jack is released, the wedge-set occurs again at the jacking end. Since the load is picked up again upon re-gripping, the wedge set of individual pulls is not cumulative. Only the final wedge set affects the loss of tendon force. However, keeping account of cumulative elongations and wedge-sets during repeated pulls by a jack is always helpful for resolving unforeseen problems.

Stressing calculations are illustrated with two examples: first for a long tendon draped to a profile through four continuous spans and stressed sequentially from both ends; second for a deviated external tendon in an end span stressed from the expansion joint.

Various parameters for calculation of stressing forces and elongations are defined as follows:

- Length of tendon (L)
- Assumed area of tendon (A_S)
- Modulus of Elasticity assumed (E_S)
- Coefficient of friction between tendon and duct (μ)
- Wobble coefficient (k)
- Distance from jacking end to location of interest = x
- Accumulated angle of curvature to point x = θ_X
- Length of portion of tendon between two points "i" and "j", = X_{ij}
- Wedge seating loss (W)
- Friction in anchor (%)
- Friction in jack (%)
- P_0 = force at the jack

In the terms A_S and E_S the subscript S signifies that these are assumed values for the purpose of the initial calculations. During stressing operations, the anticipated elongation is adjusted to account for the actual values of A_r and E_r for the reel of strand used.

The force in the tendon (P_X) at each point of interest a distance "x" from the jack is determined from the formula:

$$P_X = P_0 . e^{-(\mu\theta + kx)}$$

The total elongation is obtained by summing the increments of elongation for each portion of the tendon, based on the average of the force at the beginning and end of that portion: Elongation $\Delta L = \sum (Pav.X_{ij} / A_{S1}.E_{S1})$ where Pav = average force over X_{ij}.

Information to be forwarded to the site engineer or inspector should include:

- Tendon identification
- Assumed area of strands (A_S)
- Assumed modulus of elasticity (E_S)
- Required jacking force, P jack
- Wedge set (draw-in), W, assumed for each end of each tendon
- Calculated elongation at each end, before release of the jack and wedge set for each end of the tendon, depending upon the ends to be jacked first and second
- The anticipated total elongation, ΔL, before wedge set

Information to be adjusted on site includes:

- A_r = actual area of strands
- E_r = actual modulus from samples per strand LOT or per coil or (reel) of strand
- Total target elongation = $\Delta L * (A_s * E_s) / (A_r * E_r)$
- Anticipated elongation at each end in proportion to the adjusted target elongation

3.1.2.1 Example 1 - Four-Span, Spliced I-Girder

Consider a four-span, spliced I-girder with a gradually curving tendon profile made up of several parabolic arcs as illustrated in Figure 3.2. It is necessary to calculate the expected elongation and final post-tensioning force, allowing for friction, wobble and wedge set. Two spans of the structure are shown and it is assumed to be symmetrical about the center pier. Being a long tendon, it must be stressed from both ends or else the total force loss will be too great. However, for on-site efficiency and resources, stressing is done first at one end then the other.

The calculation is made by considering each arc of the profile in turn and applying the above formula to determine the force at the beginning and end of each portion, commencing at the jack. For convenience, the calculation is made using a spreadsheet (Tables 3.1(a) and (b) at end of this Chapter). Also, for clarity, this example is shown in customary U.S. units at this time.

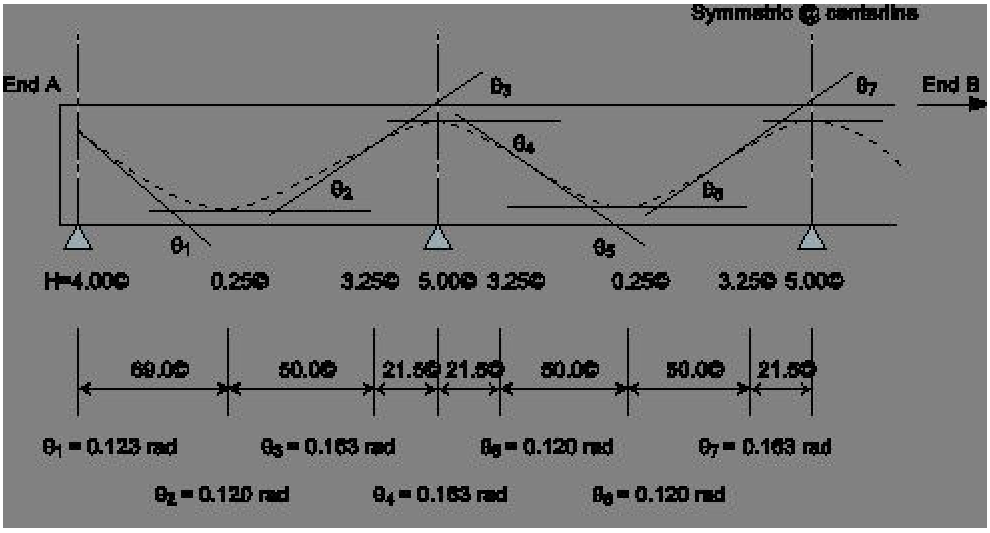


Figure 3.2 - Tendon profile in four-span I-girder

When stressed first from one end (A) (left hand end of Figure 3.2), the elongation is calculated to be 38.53 in. (Table 3.1 (a)). Two things should be observed. First, this elongation is greater than the available stroke of normal stressing jacks; so full elongation may require three or four separate pulls from this one end alone. Second, in Table 3.1(a), account is not taken of the initial wedge set at end (B) (the opposite end of the bridge). This anticipated wedge set occurs while end B is a non-stressing "dead end". In theory, it should be added to the total anticipated elongation for stressing from end A. For instance, if all of the elongation could be measured at end A, the apparent elongation at A would become 38.53 + 0.38 = 38.91 in. - if wedge set at end B is assumed to be, say, 0.38 in. However, in the field not all the force will be applied in one step at end A. In fact an initial load, usually 20%, is applied at A to remove slack and seat the wedges at end B. Elongations are only measured after this initial load. A correction is added for the initial 20% based upon that measured from 20 to 100% load.

The second stage of stressing is performed from end B. Consequently, it is necessary to calculate the anticipated (additional) elongation and final force at end B. After stressing from end A, the force in the tendon at end B is calculated to be 169.1 kips (Table 3.1(a)). Hence, when jacking at end B, the jack will not begin to move until the load exceeds this amount. The jack at B will pick up load at 169.1 kips and continue to the required jacking force of 308.0 kips.

However, because of loss due to friction and wobble, the effect of jacking at B will travel only so far along the bridge until it reaches a point where the force is equal to that from jacking at end A. In this case, because the bridge is symmetrical, this occurs at the middle pier. Consequently, the additional elongation at end B comes only from the increase in tendon force between end B and the middle pier. This elongation is calculated in Table 3.1(b) to be 6.36 in.

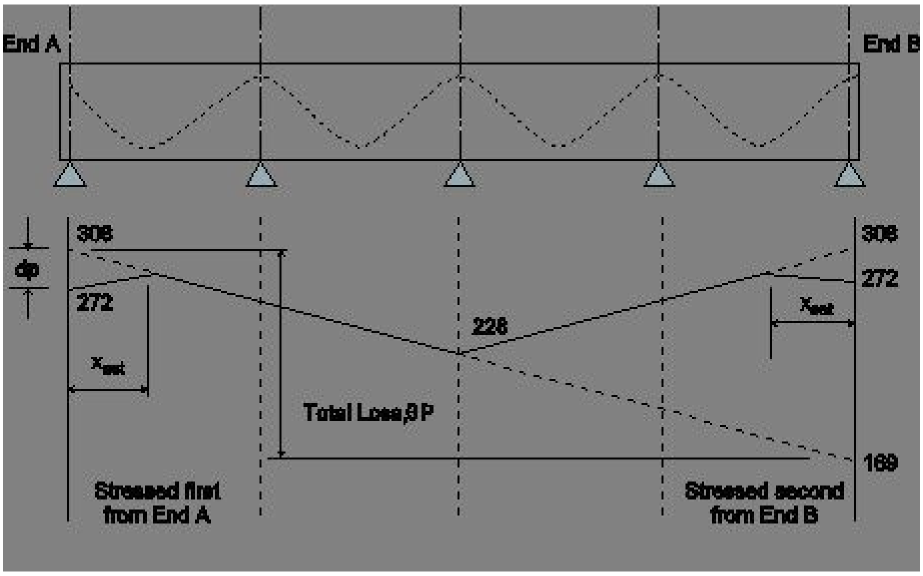


Figure 3.3 - Calculated tendon force after losses

So the total elongation of the tendon before any wedge set is:

38.53 (at A, from Table 3.1(a)) + 6.36 (at B from Table 3.1(b)) = 44.88 in.

The net elongation after wedge set at both ends is then:

44.88 - 0.38 (at A) - 0.38 (at B) = 44.12 in. (Table 3.1 (b)).

In the field, the elongation at B (6.36 in.) will be observed and measured at end B as taking place from the point to which the wedges have already been pulled in after stressing from end A. If a mark were made on the strand tails at end B before stressing from end A, it would move inwards at least by the amount of wedge set at B (0.38 in). In fact, it is likely to move more than this, especially if the wedges at B have only been initially seated "by hand". Fortunately, it is not necessary to know the initial wedge pull in at B due to load at A, because the actual elongation at B is measured from where the strand is at B only after loading from end A.

After release of the jack at B, the wedges are pulled in by the final wedge set of 0.38 in. at B. Consequently, as a check, the net total elongation after wedge set is given by (Table 3.1 (b)):

38.53 (net at end A) - 0.38 (set at B) + 5.98 (net movement at B) = 44.13 in (O.K.).

The force loss (dp) at each end is determined for the amount of anticipated wedge set as shown in Tables 3.1(a) and (b). For this example, the final, calculated Post-Tensioning force is summarized in Figure 3.3. The minimum force (228 kips) is at the center of the four span unit.

Required jacking forces and expected elongations are forwarded to the field for stressing operations. In the field these become the target forces and elongations of the field stressing report (Tables 3.3(a) and (b) at end of this Chapter).

It should be noted that in this example, no account has been taken for the elastic shortening of the structure under the axial compression force of the tendon. If this stressing is performed only on the girder before any deck slab has been cast and if the above tendon is the first of several, then the elastic shortening is estimated approximately as follows:

From Figure 3.3 the average force, P, in the girder is 264.6 kips. If the cross section area of the girder is $A_C = 6.00$ ft^2, and assuming an initial modulus of elasticity of 4,500 ksi and total bridge length is $L_B = 567$ ft., the elastic shortening is given by $x_{EL} = PL_B / A_C E_C = 0.46$ in.

This is relatively small. However, in the field, it would have the effect of increasing the measured elongations; approximately in proportion to the calculated elongation at each end. After a deck slab has been added, elastic shortening from a similar tendon would be much less.

It follows that stressing of a subsequent tendon of the same profile would result in the same elongations for that tendon. However, it also follows that elastic shortening caused by stressing of a second tendon reduces the effective force in the first tendon. Such reduction also occurs for the effect of all subsequent tendons stressed after earlier ones. The effect of such staged post-tensioning is normally taken into account by the Designer during design of the bridge. The Designer should consider the effects of elastic shortening in the design of post-tensioning forces.

3.1.2.2 Example 2 - External Deviated Tendon in End Span

Consider the external tendon in the end-span of a typical span-by-span bridge (Figure 3.4). In this case, the tendon is stressed from one end only (right hand end). It is necessary to calculate the anticipated force in the tendon after stressing, the elongation and effect of wedge set.

Friction between the tendon and duct can only occur at deviators and in those portions of duct in the diaphragms of pier or expansion joint segments where the tendon path curves to an anchor. In this example, there is a curve at the dead end only and none at the stressing end. Curvature friction, μ, applies at the deviators and the dead end diaphragm. There is no loss due to wobble in external tendons, so k = zero.

For the purpose of calculation, the tendon is considered in individual portions, either external or internal and the force loss is calculated according to the same formula as above, i.e:

$P_X = P_0 . e^{-(\mu\theta + kx)}$

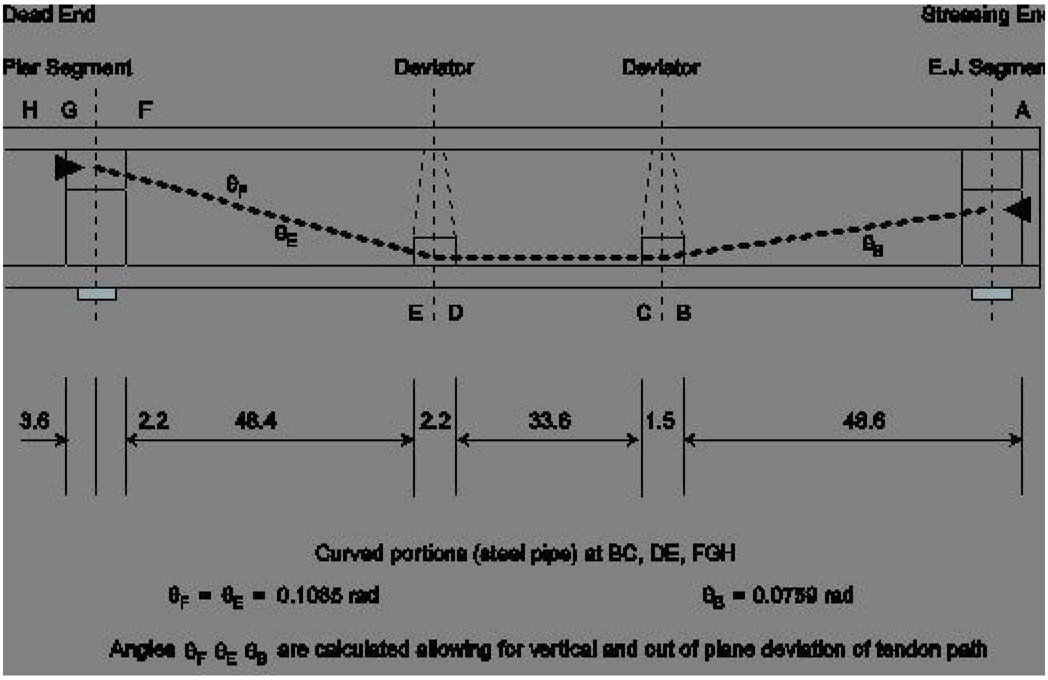


Figure 3.4 - External Deviated Tendon in End Span

For convenience, the calculation is performed using a spreadsheet (Table 3.2). Also, for clarity, this example is shown in customary U.S. units at this time. The force at each point along the tendon is determined for the condition just before the jack is released. The total elongation at jacking is the summation of the elongation for each portion.

The effect of wedge set is not as easily determined as for a continuous, internal tendon of Example 1. Rather, it is necessary to determine if the effect of wedge set terminates within the first deviator (BC) or if it extends to the next deviator or beyond. This may be done by first making the assumption that the wedge set effect terminates at the first deviator and then calculating the force that should exist in the other portions of the tendon if this were the case, and comparing it to the original force at jacking before wedge set loss.

In this example, we find that the force in AB reduces significantly from 835 to 761 kips. It follows that the force in portion CD must be greater than that in AB but cannot be more than that due to friction loss through deviator BC. Hence the force in CD would have to be 761+ (835-819) = 775kips. But, because the original jacking force in CD of 819 kips is greater than 775, it follows that deviator BC alone cannot absorb all of the loss due to wedge set. Hence wedge set must also affect portion CD.

The calculation is repeated, this time assuming that the wedge set terminates in deviator DE. This time, we find that the force in AB is 792 kips and in CD is 807 kips. Because the difference in force in portions CD and EF (i.e. 807-797 = 10 kips) is less than the original friction loss of 22 kips across deviator DE, it follows that the effect of wedge set terminates at DE. The final force diagram after friction and wedge set loss jacking is then known (Figure 3.5). In this case, the final force is nearly uniform (approximately 800 kips) along the tendon.

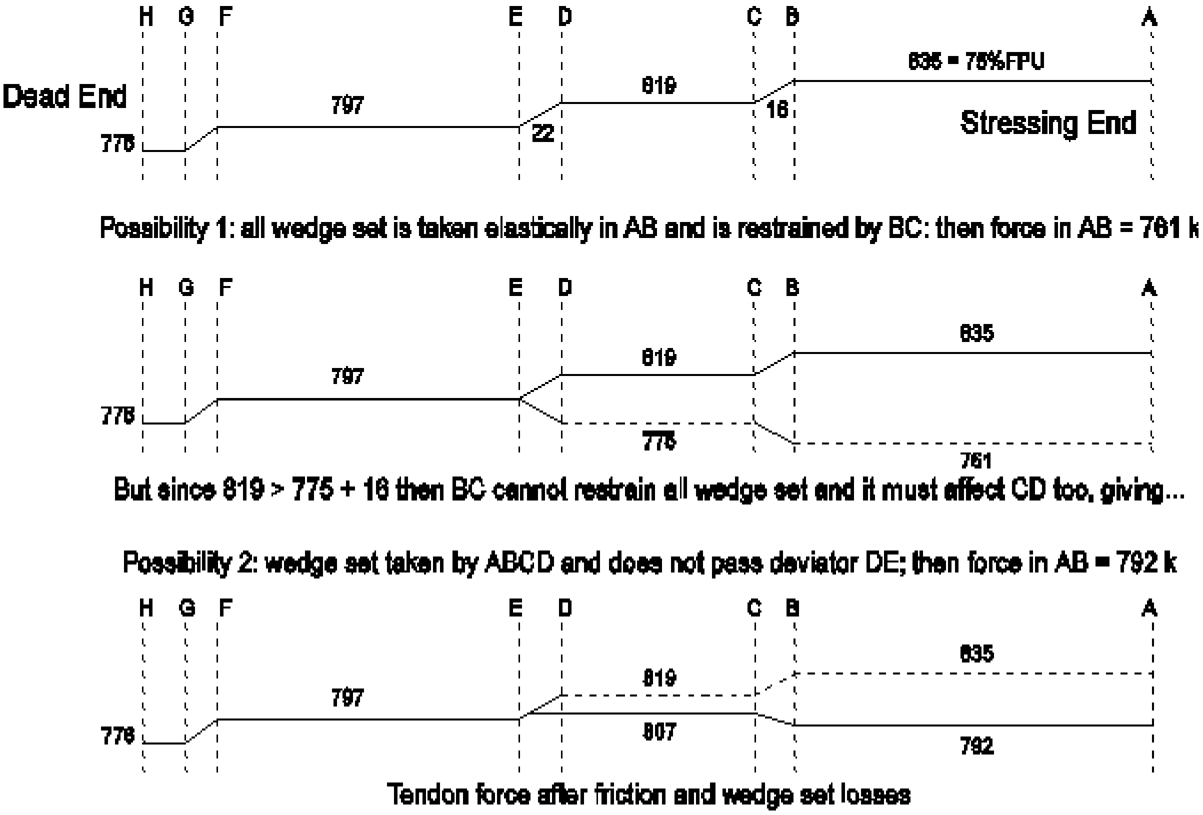


Figure 3.5 - External Tendon Force after Friction and Wedge Set

3.2 Tendon Testing On Site

3.2.1 Friction

The purpose of a friction test is to verify the assumptions for the coefficients of friction and wobble. This test would be appropriate for all but small scale applications where it would suffice to adopt friction and wobble values from other, previous, experience.

A friction test is normally performed on a typical tendon representative of the type or group of tendons being installed - for example, on one tendon in one girder of several in the span or on perhaps two similar cantilever tendons in the top of precast or cast-in-place segments.

For any tendon, there are two unknowns, the coefficients of friction (μ) and wobble (k).However, for any given test set up where the force is measured at each end of the tendon, there can only be one equation and result based upon the standard force loss equation:

$$P_X = P_0 . e^{-(\mu\theta + kx)}$$

Consequently, two unknowns (μ and k) have to be derived from one equation. This is not possible unless one of the unknowns is already known.

For an external tendon in, say a span-by-span bridge, (Figure 3.4) the points of curvature are relatively discrete and the angles consumed are known. In the straight portions there is no wobble. So in such a case, providing that the pre-curved steel pipe ducts in the pier diaphragms and deviator saddles have been correctly installed, then it may be assumed that k

= 0. Thus a test on this type of tendon should provide a reasonable result for the effective coefficient of friction, μ, between the tendon and the steel pipes.

For a tendon in the top of a segmental precast or cast-in-place cantilever (Figure 3.6), usually the alignment is relatively, but not completely, straight between two curves at each end anchor. If the duct for this type of tendon has been carefully and well installed so that there is no wobble, then it may be assumed that k = 0 and a test should provide a reasonable result for μ.

On the other hand, if there is uncertainty as to how well a duct has been installed or if it is known to have significant unintentional wobble, it is necessary to make a judgment as to a suitable proportion of loss due to friction and loss due to wobble. It is suggested that the wobble coefficient be taken as the assumed value for "k" - and use the test result to give "μ".

An alternative approach to determine both coefficients μ and k would be to perform the friction test on two similar, say cantilever tendons - a short one and a long one. Assuming the tendons are installed with the same materials and standard of care, this would provide two independent results (i.e. two equations) which could be solved simultaneously for μ and k.

In any event, it is recommended that each friction test be performed on at least two, very similar or identical, tendons - of the same length and curvature layout - for example, in a segmental cantilever, one tendon over the left web and its counterpart over the right web. The average of the pair represents one result (i.e. one equation). In an I-girder with a continuously draped tendon profile, the two tests could be performed on two very similar tendons in the same girder or the same profile of tendon in two parallel girders - where again, the average of the two represents one result (equation).

In general, friction testing is likely to give reasonable results only on relatively long tendons (over about 30M (100 ft)) since it is necessary to measure both forces and elongations under incremental loading to a sufficient level of accuracy. For this reason, an in-place friction test is not appropriate for some applications such as, straight longitudinal or transverse tendons in "flat-oval" ducts or similar in voided precast slabs or transverse deck slab tendons in precast or cast-in-place segments.

It is usual to test a minimum of one tendon in a group of tendons performing the same function - e.g. one tendon in each web of a two-web box. Tendon function may be generally described as:

- Internal cantilever tendon or continuity tendon (e.g. in precast or cip segments)
- External draped (deviated) tendon (e.g. in span-by-span construction)
- Profiled (draped) internal tendon (e.g. I-girders and cip boxes)

Selected tendons should represent the general size (that is number of strands) and length. It is recommended that friction test groups be identified on Shop Drawings for approval.

The test procedure is to tension the tendon at one anchor assembly and measure the force at the dead end using a load cell or calibrated jack. The tendon should be tensioned to 80% of ultimate in increments of not less than 20%. For each increment, the gauge pressure at the jacking end, the load cell (or jack) force at the dead end and the elongation at the jacking end should be recorded. Also, note the wedge pull-in at both ends. Take into account the loss of force due to friction in the anchorages and wedge plates as the strands deviate slightly through them and any friction in the jack. The manufacturer of the post-tensioning system should be able to provide percentage estimates for these losses. For very long tendons that require multiple jack pulls, it is essential to keep an accurate account of elongation at the jacking end and each corresponding intermediate wedge set (pull-in).

If wedges are not installed, and if the available jacking equipment can facilitate it, forces and elongations measured while gradually releasing the jacking load should reveal a lag or hysteresis resulting from the reverse effect of friction (Fig. 3.6). The force and elongation may not immediately return to zero due to residual friction effects.

When performing friction tests, it is recommended that forces and elongations be reconciled within a tolerance of 5% for all tendons. The 5% to 7% tolerance in AASHTO LRFD Construction Specifications is for production tendon elongations - no guidance is given for friction tests.

If the total measured elongation is different to the anticipated (calculated) elongation by more than 5% then the reasons for it should be investigated. It may be necessary to make more detailed calculations or to run a similar test on another tendon. It is suggested that assumed values for friction (μ) and wobble (k) not be varied by more than 10% when attempting to reconcile measured and anticipated results.

A significant shortfall in elongation is indicative of poor duct alignments or obstructions. The likely causes should be examined and appropriate corrective measures taken.

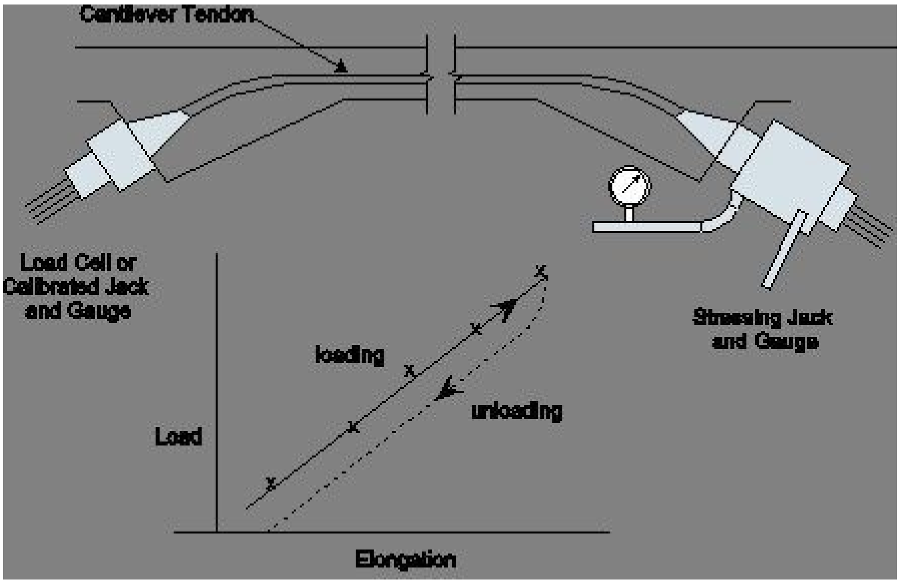


Figure 3.6 - On-site Friction Test

3.2.2 Modulus of Elasticity

The modulus of elasticity, E, is provided per coil of strand, or bundle of bars for each of the manufacturers lots. This is derived from proof tests performed by the manufacturer as part of his quality control of the strand, or bar, production.

The modulus of elasticity for an individual strand is generally about 193 to 200GPa (28,000 to 29,000 ksi.) There is a school of thought that the effective modulus of elasticity of a bundle of strands made up into a multi-strand tendon may be slightly less than that of an individual strand because of the bundle effect or the "un-wrapping", if any, as strands are stressed. This is not necessarily so. In some bench-tests performed on an approximate gauge length of 9M (30 feet) with no contact between tendon and duct, the modulus of the group of strands proved to be the same as that of an individual strand once appropriate allowance was made for losses in the jack and anchors. Therefore it is recommended that calculations of elongations be based upon appropriate assumed or actual production values for strand only. It is also recommended that when calculating elongations, proper allowances be made for all force loss effects.

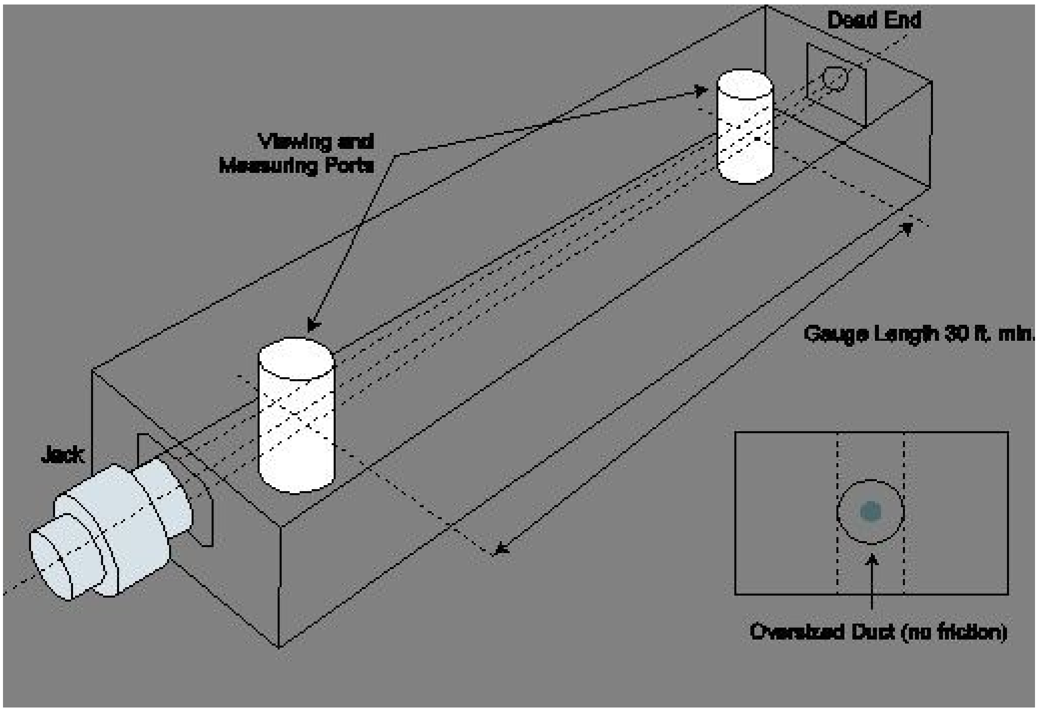


Figure 3.7 - On-site Bench Test for Modulus of Elasticity

A typical set-up for a bench test to check the modulus of elasticity of a tendon made of a bundle of strands is illustrated in Figure 3.7 which may be used for guidance if the project documents require bench tests. It is recommended that the number, frequency and details for bench tests be proposed for approval on the Shop Drawings. The following number of tests is suggested for guidance:

- For small projects with less than approximately 45T (100,000 lbs) of PT: no bench tests, providing that strands are from the same supplier with certified copies of proof of modulus from production sampling and testing.
- For larger projects: one per 45T (100,000 lbs) of PT: one test if from the same supplier or one test per each supplier.

3.3 Anchorages and Anchor Components

3.3.1 Standard or Basic Anchor Bearing Plate

Early post-tensioning anchors for strand tendons consisted of a simple rectangular or square steel bearing plate supporting a wedge plate (Figure 3.8). The flare of the strands is accommodated within a cone or trumpet attached to the back of the bearing plate. The cone is made of galvanized sheet metal or plastic. Nowadays, these simple types of bearing plates have mostly been superseded by multi-plane anchors or special composite anchor systems.

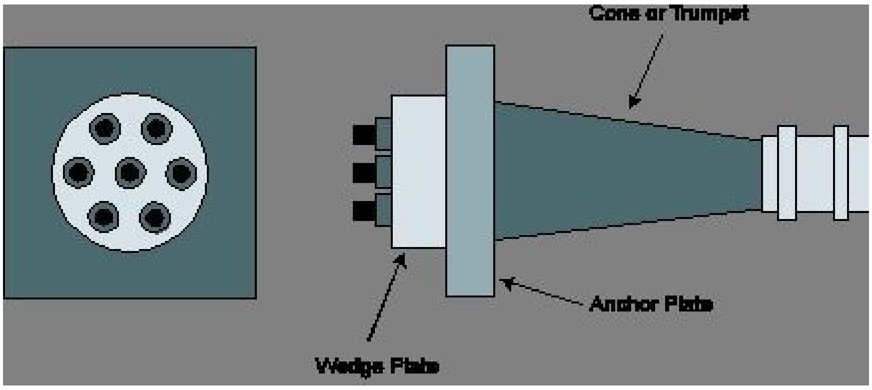


Figure 3.8 - Basic Anchor Bearing Plate

Basic anchor plates are usually sized according to formulae of AASHTO LRFD Bridge Design Specifications. Simple, flat bearing plates are still used for bar tendons, especially for temporary post-tensioning.

3.3.2 Multi-Plane Anchor

Multi-plane anchors (Figure 3.9) induce local bearing stress greater than the limit allowed for standard (basic bearing plate) plate. Therefore, multi-plane anchors need special reinforcement for confinement of the local anchor zone.This is normally supplied by the manufacturer of the anchor - usually in the form of a spiral (not shown).

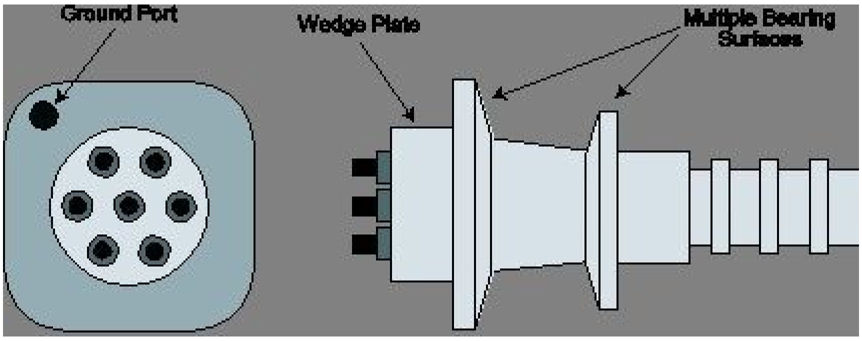


Figure 3.9 - Multi-plane Anchor

3.3.3 Special (Composite) Anchor Plates

Some manufacturers have introduced special composite anchors. These require special local zone confinement reinforcing similar to multi-plane anchors.

3.3.4 Anchor Plates for Bar Tendons

Anchor plates for bar tendons are usually square or rectangular (Figure 3.10). A separate bearing plate is used for each bar. Other types of confined,circular, anchors are also available.

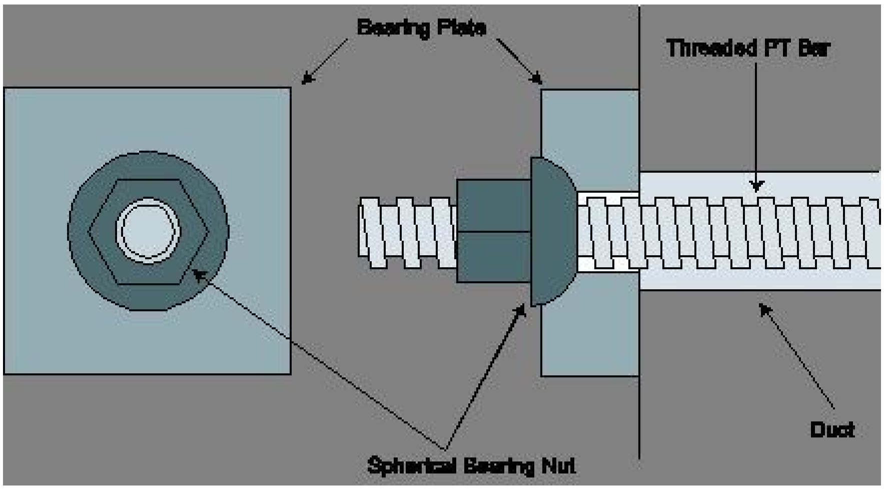


Figure 3.10 - Anchor Plate for PT-Bar

3.3.5 Local Zone Reinforcement

Regardless of the type of anchor, it is essential to provide reinforcement in the local anchor zone - this is the region directly behind the anchor bearing plate(s). For longitudinal strand tendons, mostly, this usually comprises a spiral (Figure 3.11). Grids or rectangular links may be used instead of or to supplement spiral reinforcing. Local zone reinforcement should be placed as close as possible (i.e. 12mm (1/2 inch) maximum) to the main anchor plate in all applications.

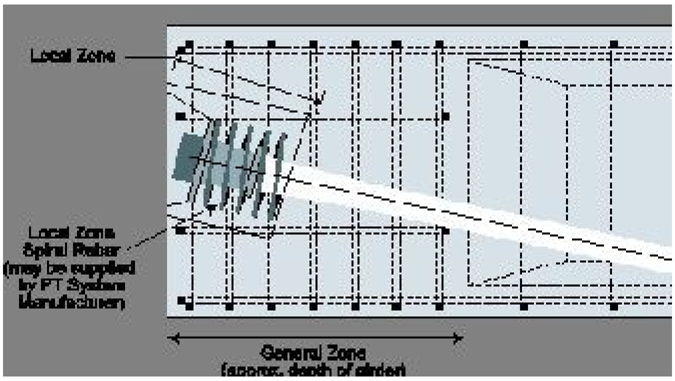


Figure 3.11 - General and Local Anchor Zone in End of I-Girder

A series of relatively closely spaced rectangular stirrups is normally provided to reinforce the general anchor zone (region around and beyond the local zone) until the local anchor force has dispersed to the full effective depth of the section. Typically, for an I-girder, this extends over a length approximately equal to the depth of the beam from the anchor.

Local anchor zones for transverse deck slab tendons anchored in the relatively shallow depth at the edge of segments are most effectively reinforced by multiple-U shaped bars placed in alternating up and down arrangement, beginning very close to the anchor plate (Figure 3.12).

This arrangement has been found to be very effective for intercepting potential cracks that might originate at the top or bottom corner of the anchor bearing plate and travel diagonally through the adjacent surface - apart from the classical splitting stress along the line of the tendon itself.

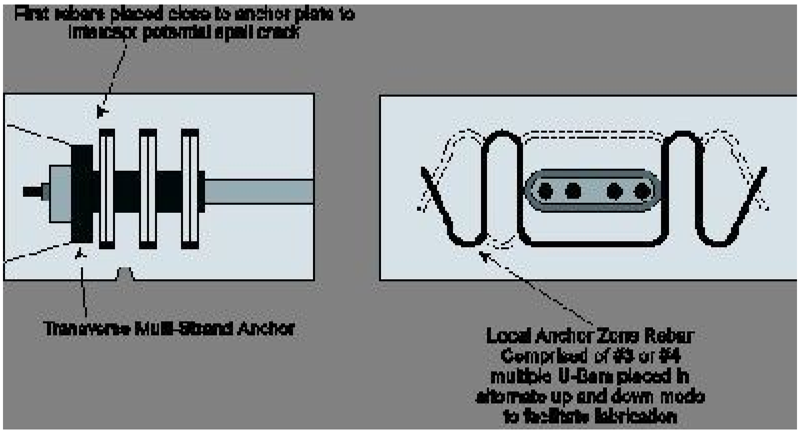


Figure 3.12 - Local zone reinforcing for edge anchor in thin slab

3.4 Duct Installation

3.4.1 Alignment

Correct duct alignment and profile is of paramount importance to the proper functioning of a post-tensioning tendon, whether that tendon is internal or external to the concrete. Duct alignment and profile should be clearly and sufficiently defined on the plans and approved shop drawings by dimensions to tangent points, radii, angles and offsets to fixed surfaces or established reference lines and by entry and exit locations and angles at anchorage or intermediate bulkheads. Alignment, spacing, clearance and details should be in accordance with AASHTO LRFD Specifications 5.10.3.3 thru 5.10.4.3.2.

General recommendations for fabrication are that ducts should be:

- Installed to correct profile (line and level) within specified tolerances
- Tied and properly supported at frequent intervals
- Connected with positively sealed couplings between pieces of duct and between ducts and anchors
- Aligned with sealed couplers at temporary bulkheads
- Positively sealed at connections made on-site and in cast-in-place splice joints
- The elevations and alignments of ducts should be carefully checked

3.4.1.1 Ducts for Internal Tendons: I-Girders and Cast-in-Place Construction

Recommendations for ducts in concrete in I-girders (Figure 3.13):

- Maximum allowable size of aggregate should be specified
- The distance between the outside of the duct and the side of the web should be adequate to accommodate the vertical reinforcing and specified

cover and provide the minimum concrete section to satisfy design requirements.

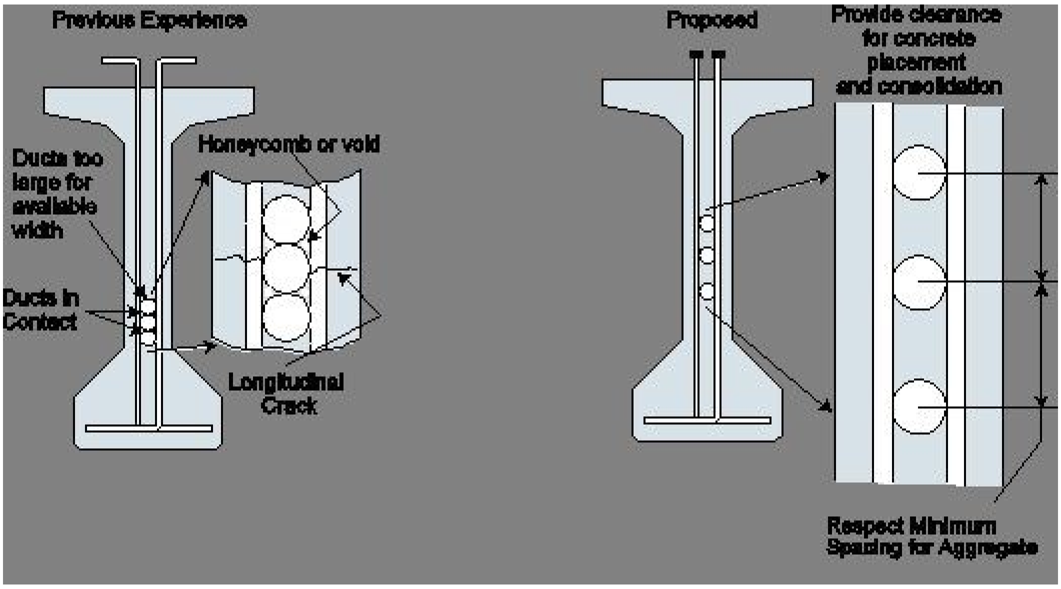


Figure 3.13 - Duct spacing and clearance in post-tensioned precast girders

3.4.1.2 Ducts for Internal Tendons in Precast Segments:

In addition to the above general recommendations ducts should be:

- Installed to connect correct duct location in bulkhead with correct duct location in match-cast segment
- Correctly aligned with respect to the orientation of the segment in the casting cell and the direction of erection
- Elevations and alignments of longitudinal and transverse ducts should be carefully checked (Fig. 3.14)

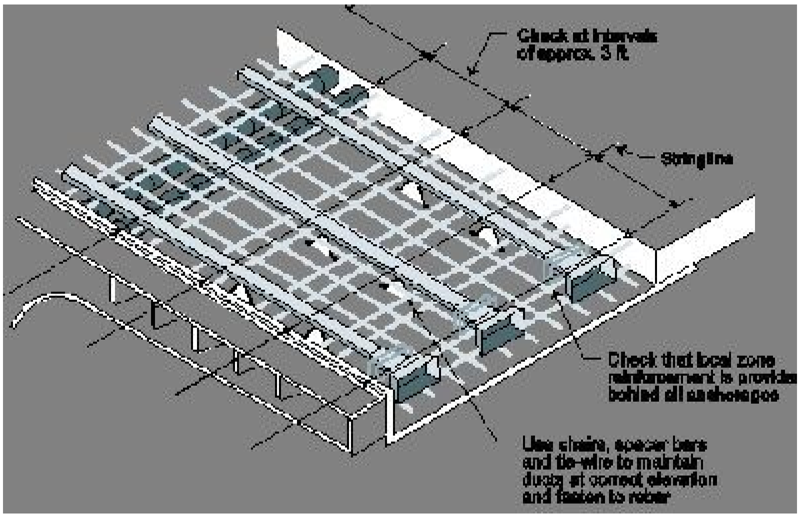


Figure 3.14 - Check longitudinal and transverse duct alignments

3.4.1.3 Ducts for External Tendons in Cast-in-Place and Precast Segments:

In addition to the above general recommendations, during erection:

- Ducts should have positively sealed connections between external duct and steel pipes and between individual lengths of duct*
- When installing HDPE pipes to connect with deviator and diaphragm pipes,installation should be checked to make sure the correct tendons are connected
- Joints between match-cast segments should be properly prepared and sealed with epoxy as necessary according to the specific project contract requirements

*Duct tape does not qualify as a seal although it may be used for temporary support purposes.

3.4.1.4 Alignment at Anchors

For both internal and external tendons, anchors should be:

- The correct type and size for the type and size of tendon used.
- When required, supplied with permanent, heavy duty, plastic caps with a seal against the anchor plate.
- Properly aligned and well supported by formwork.
- When required, set in a recess (anchor pocket or block-out) of correct size, shape and set to orientation.
- Provided with correct local and general zone reinforcement at correct location and spacing.

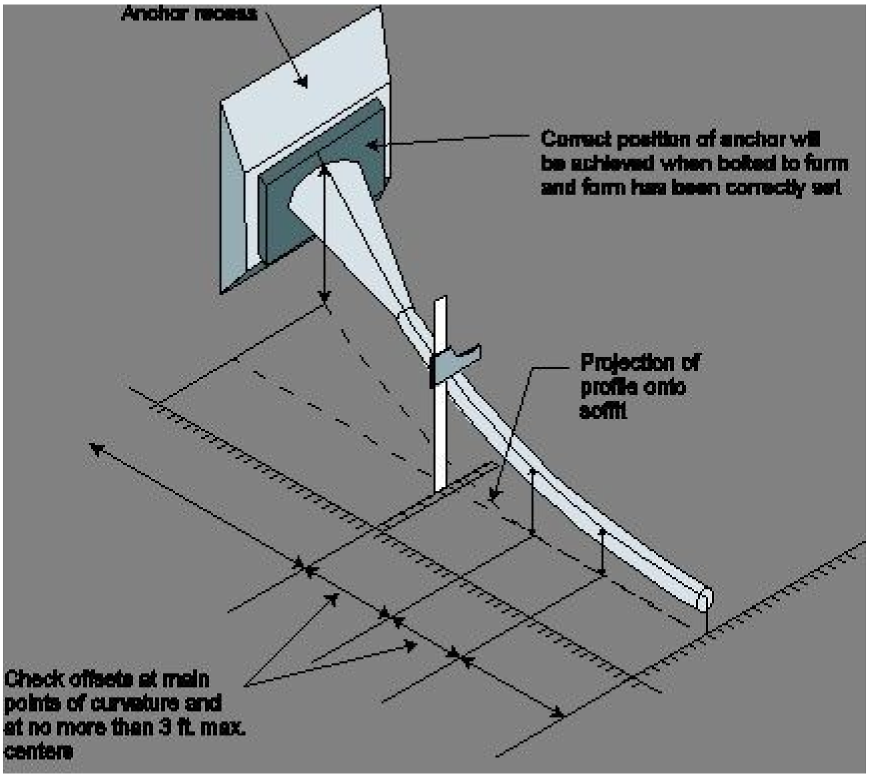


Figure 3.15 - Anchor recess and checking of duct alignment

Sometimes it is necessary to check an alignment in three dimensions from fixed surfaces or reference lines (e.g. centerlines), for example, as indicated in Fig. 3.15.

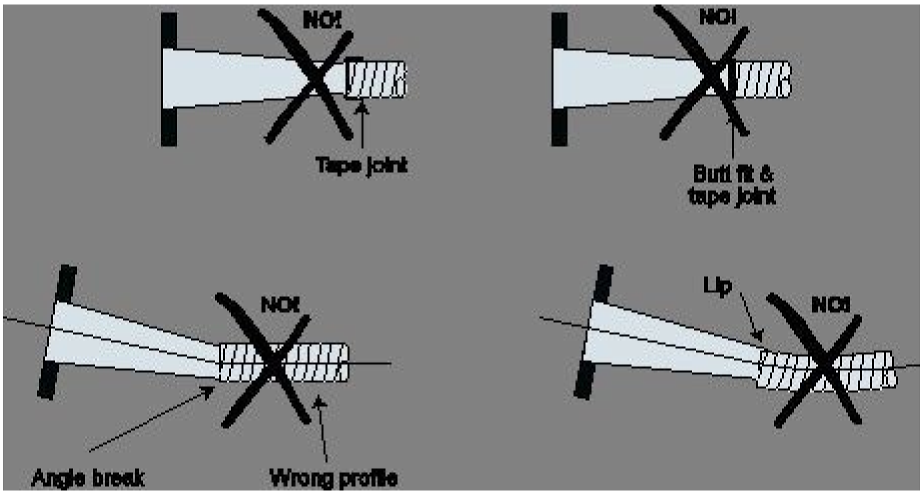


Figure 3.16 - Unacceptable Duct Connections and Mistakes

A good connection of the duct to an anchor should make a seal and properly align the duct with the anchor. Examples of poor practice and potential risks are shown in Figure 3.16.

Nowadays, commercial systems generally offer a positive, sealed and aligned connection.

3.4.1.5 Cover

Cover is an integral part of corrosion protection. Cover should be checked to rebar and longitudinal and transverse post-tensioning ducts.

3.4.2 Duct Supports

In order to secure post-tensioning ducts to a profile, prevent floatation, or displacement or disconnection, supports should be provided at frequent intervals (Figure 3.17).

- Duct supports may be tie-wire, rebar, D4 wire tied to web reinforcing, or an approved commercial device. Use of tie-wire alone is satisfactory providing that it is not tightened so much as to distort the rebar cage or crimp the duct
- Support bars may be straight, L, U or Z-shape reinforcing bar as necessary
- Supports should be at intervals of no more than 0.6 to 1.0M (2 to 3 feet),or per recommendations of duct supplier.
- Minimum cover and clearances should be maintained.

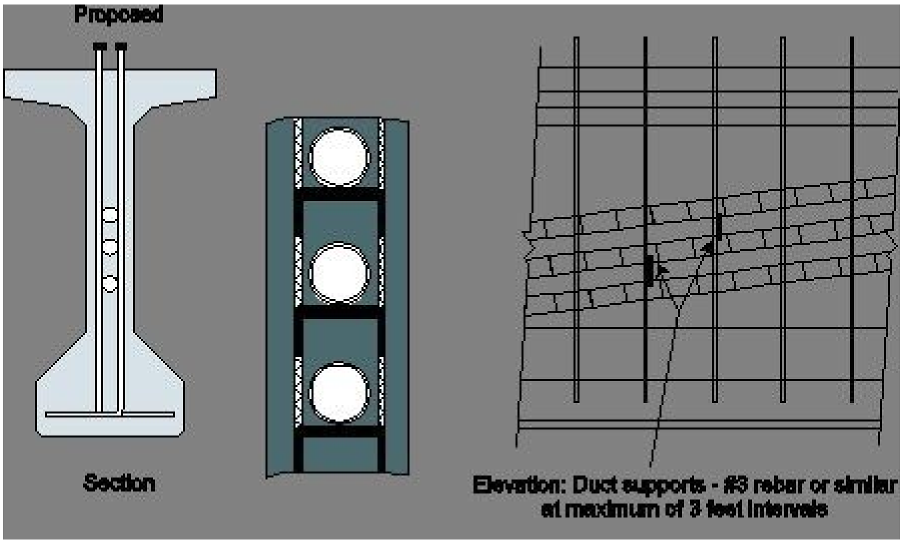


Figure 3.17 - Duct supports in post-tensioned precast I-griders

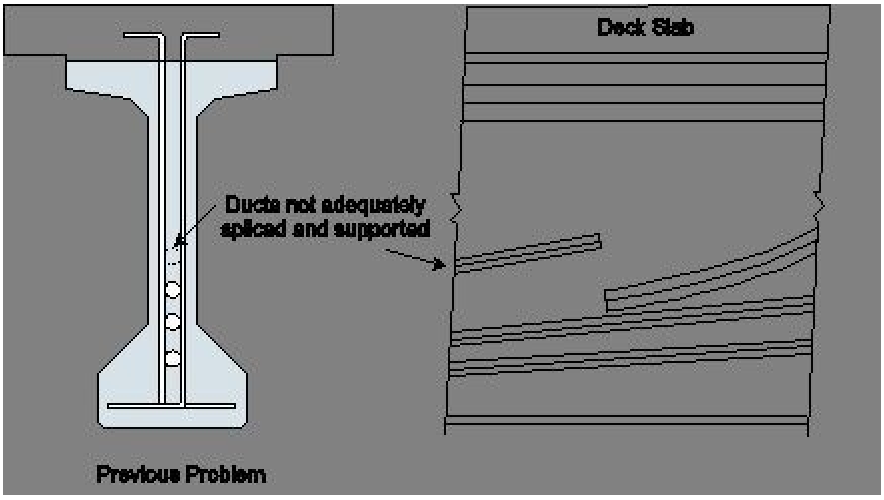


Figure 3.18 - A possible result of poorly supported and connected ducts

3.4.3 Splices and Connections

In the past, various methods were used to connect separate pieces of duct depending upon the type of duct (e.g. spiral wound, semi-rigid or flexible, corrugated or smooth, steel or plastic ducts) and to connect ducts to anchors. Often, connections were made using an oversized piece of the same duct wrapped around and secured with tie-wire or duct tape. Connections were also made solely with duct tape. Such connections are not sealed. They allow the migration of moisture or chlorides; possibly eventually leading to corrosion. Duct tape should not be used to join or repair ducts or make connections

Traditionally, galvanized steel ducts have provided some degree of sacrificial passive protection. In recent years, there has been a shift to more robust systems comprising impermeable plastic ducts, usually of high density polyethylene (HDPE) or high density polypropylene (HDPP) with purpose-made (sealed) connections; usually an outer plastic duct connector clips tightly around the duct.

Consequently, it is recommended that positively sealed connections be made between ducts and anchors and between separate pieces of duct. It is important to make sure that supports do not fail and connections do not separate during casting (Figure 3.18).

3.4.4 Grout Inlets and Outlets

It is recommended that locations for grout inlets and outlets be shown on the Shop Drawings or in a Grouting Plan for approval. Examples of recommended locations for grout inlets and outlets are given in Chapter 4.

3.4.5 Size of Pipes for Grout Inlets, Outlets and Drains

Pipes for grout inlets and outlet vents should be of sufficient diameter to allow the escape of air, water, bleed-water and the free flow of grout.

Grout pipes should be connected to ducts and anchor components in a manner that creates a seal and does not allow leaks or ingress of water, chlorides or other corrosive agents.

To facilitate inspection and complete filling of a tendon with grout, grout vents at high points (crests) may exit the top (riding) surface providing that the grout outlet vent can be properly capped and sealed. Alternatively, the outlet should exit another suitable surface. It is recommended that caps and seals be provided at all inlet and outlet vents to prevent ingress of water or corrosive agents into the tendon.

3.4.6 Positive Shut-Offs

Positive shut-off valves or other approved means of closing grout inlets and outlets should be provided at all vents. At high points or other locations, where it is suspected that air or water voids could accumulate and require filling by secondary vacuum assisted grouting, suitable connections and valves should be provided (Figure 3.19).

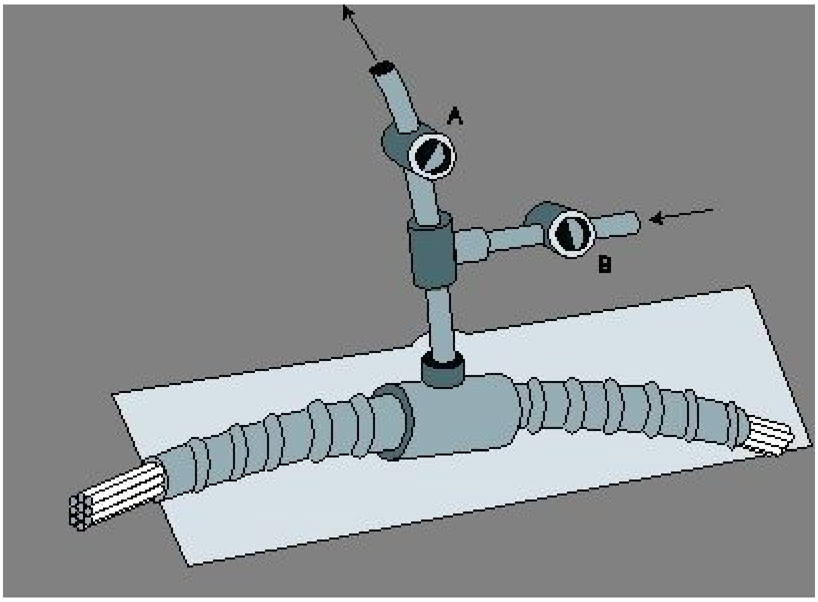


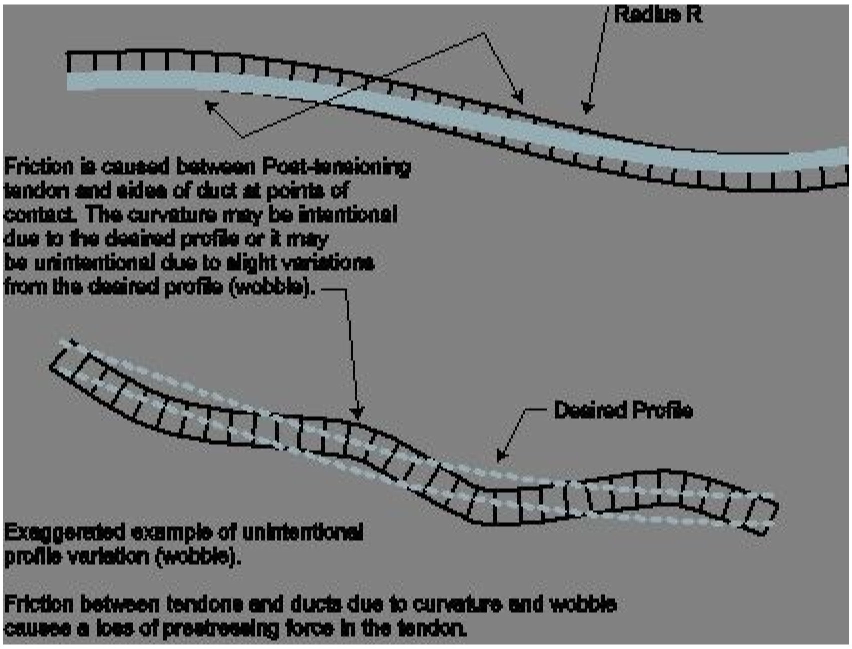
Figure 3.19 - Connections for secondary, vacuum grouting, operations

3.4.7 Protection of Ducts during Concrete Placement

3.4.7.1 Concrete Pressure

Wet concrete when discharged into forms and consolidated by vibration can exert significant pressure and local forces on reinforcing cages and post-tensioning ducts. It is essential that reinforcing cages be securely tied and held firmly in place by cover, spacer blocks or chairs. Likewise post-tensioning ducts must be well supported and attached to the reinforcing cage at frequent intervals.

Ducts, being hollow, tend to float. A duct that is not well secured can easily be displaced resulting in excess wobble (Figure 3.20). This affects the intended location of the post-tensioning tendon and causes a loss of force through excess friction. The result is a reduction in post-tensioning force and eccentricity. In some cases, excessive wobble, or improperly aligned duct (for example, Figure 2.21), can make it difficult or impossible to install a tendon.

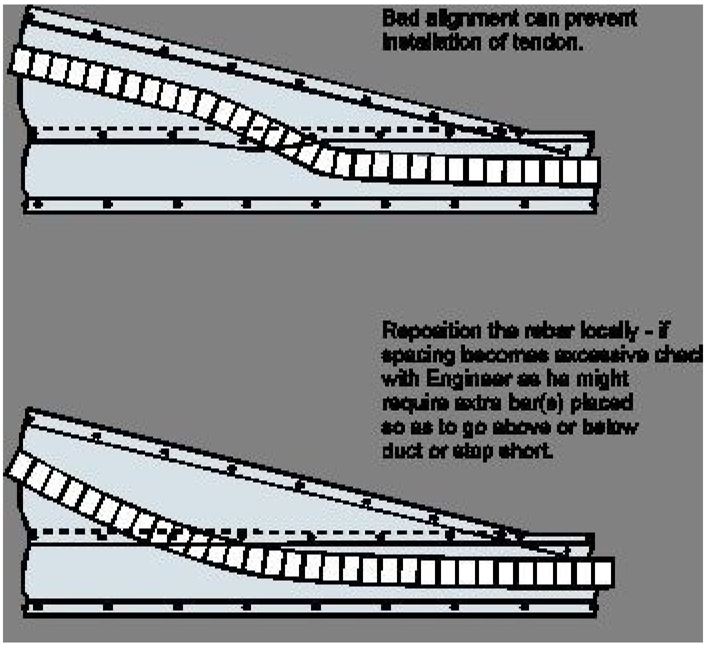


Friction is caused between Post-tensioning tendon and sides of duct at points of contact. The curvature may be intentional due to the desired profile or it may be unintentional due to slight variations from the desired profile (wobble).

Exaggerated example of unintentional profile variation (wobble).

Friction between tendons and ducts due to curvature and wobble causes a loss of prestressing force in the tendon.

Figure 3.20 - Unintentional excess wobble



Bad alignment can prevent installation of tendon.

Reposition the rebar locally - if spacing becomes excessive chec with Engineer as he might require extra bar(s) placed so as to go above or below duct or stop short.

Figure 3.21 - Excess wobble due to rebar and duct conflict

Concrete pressure itself is readily sustained by circular ducts. "Flat oval" type plastic ducts are stiffened by corrugated ribs to prevent crushing from the static or dynamic pressure of wet concrete. Placing a flat oval duct vertically in a web has resulted in local deformation of the duct wall from concrete placement and reinforcement, causing difficulties with installing tendons and local spalling (Figure 3.22). It is recommended that circular ducts be used in webs and that sufficient space be provided for concrete to flow between ducts.

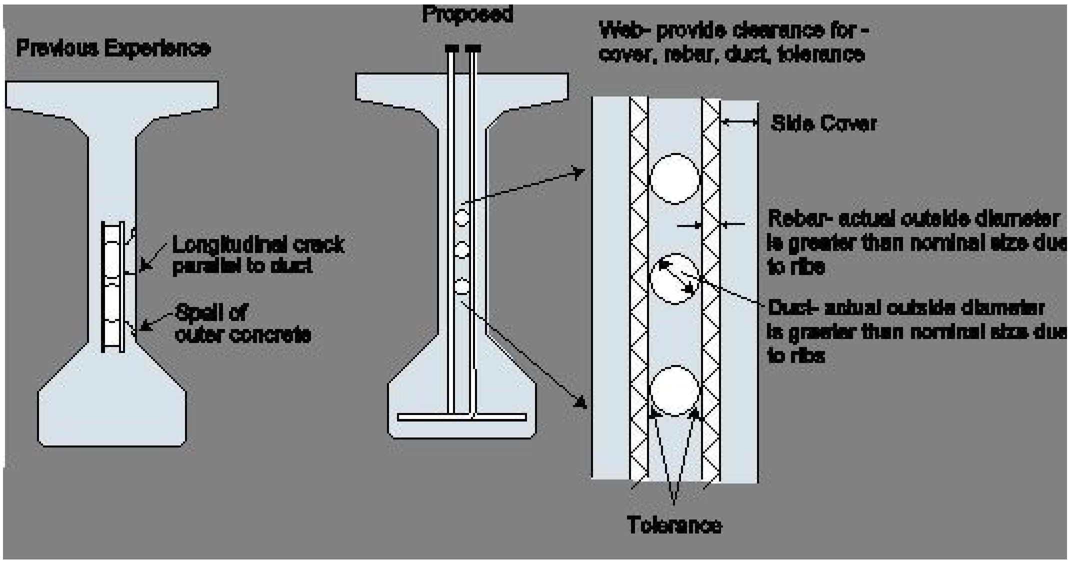


Figure 3.22 - Duct size in post-tensioned girders

3.4.7.2 Movement of Concrete

Discharge and placement of concrete can easily displace improperly secured ducts. Ducts should be properly secured and caution exercised when placing concrete. Figure 3.23 shows a case where concrete was placed down the webs and allowed to flow across the bottom slab of a segment where ducts were not well tied. The concrete displaced the ducts sideways and lead to significant difficulties with tendon installation. More duct supports, in this case between the top and bottom rebar in the bottom slab, and a change to the sequence of discharge and placement will solve this problem.

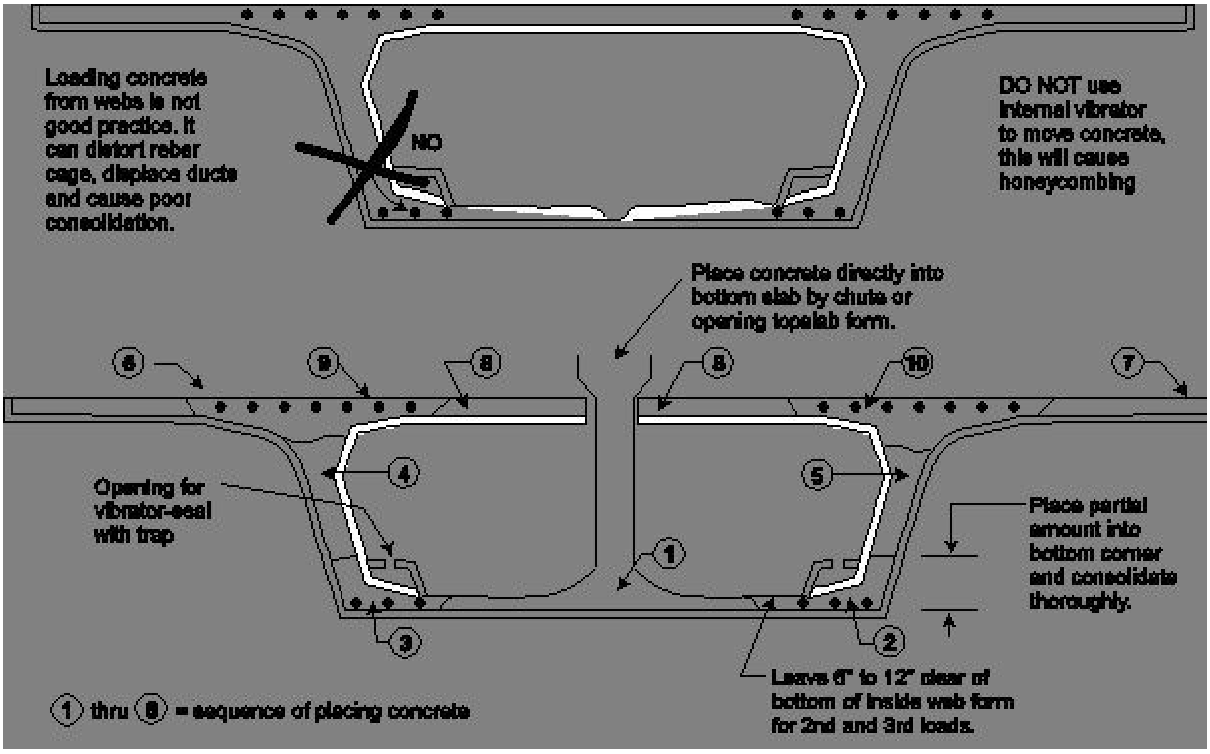
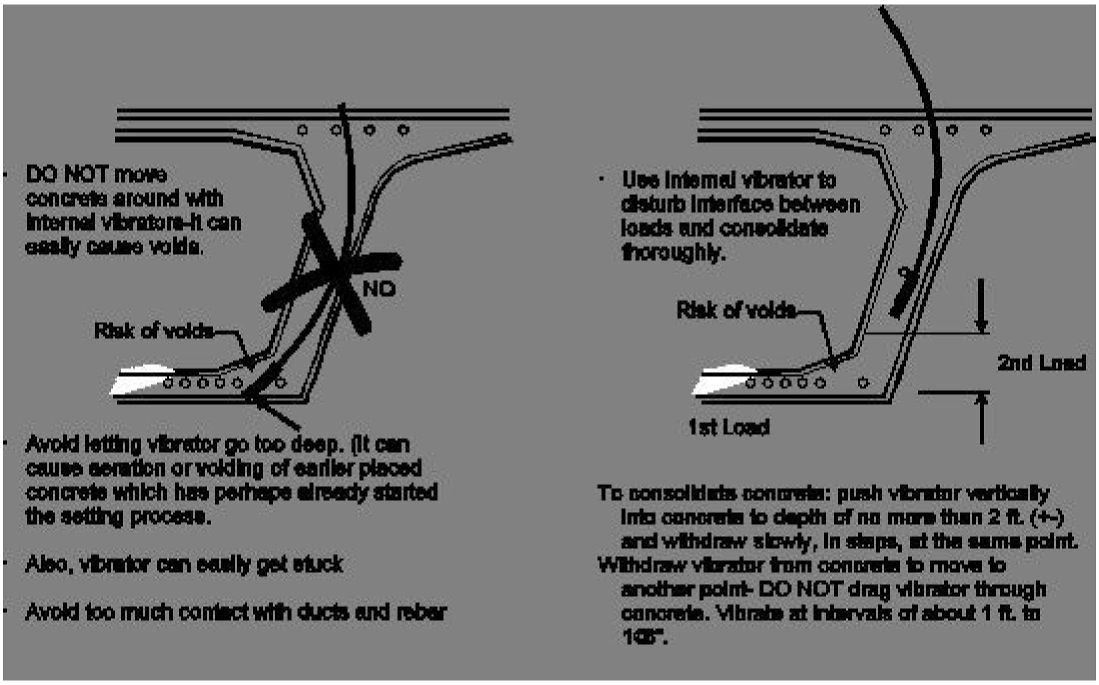


Figure 3.23 - Placing concrete in box segments

3.4.7.3 Vibration of Concrete

It is common practice to use form vibrators for concrete consolidation for many precast components such as piles and I-girders. External form vibrators may be used on casting cells for precast segments. However for most cast-in-place, and some precast, construction internal vibrators are usually needed.

Vibrators can displace ducts when they are not properly secured. Also, over aggressive or improper use of internal vibrators may lead to local duct deformation or damage. Care must be exercised. Place concrete in relatively small lifts of only two to three feet and allow internal vibrators to only penetrate sufficient to consolidate the lifts. Use care not to get a vibrator permanently lodged in the rebar cage (Figure 3.24)!



- DO NOT move concrete around with internal vibrators-it can easily cause voids.
- Avoid letting vibrator go too deep. (It can cause aeration or voiding of earlier placed concrete which has perhaps already started the setting process.
- Also, vibrator can easily get stuck
- Avoid too much contact with ducts and rebar

- Use internal vibrator to disturb interface between loads and consolidate thoroughly.

To consolidate concrete: push vibrator vertically into concrete to depth of no more than 2 ft. (+-) and withdraw slowly, in steps, at the same point. Withdraw vibrator from concrete to move to another point- DO NOT drag vibrator through concrete. Vibrate at intervals of about 1 ft. to 1.5'.

Figure 3.24 - Use of internal vibrators for consolidation of concrete

3.4.8 Protection of Ducts after Concrete Placement

To prevent unnecessary and unwanted contamination of ducts in the period from casting to installing tendons, it is strongly recommended that suitable protection measures be implemented. For example, cover or temporarily plug open ends of ducts or install temporary caps over anchors to prevent water and vermin entering them. Drain holes in the bottom of ducts should be left open with grout pipes pointing downward to freely drain any rain water or condensation. Grout vents at high points and anchors should be temporarily closed. Areas of faces of components such as precast segments with multiple duct openings may be covered with suitable heavy duty plastic sheet. All temporary measures should be periodically checked, particularly if work is partially finished or components are in storage for extended periods.

Relatively simple precautions are worthwhile compared to the inconvenience and potential costs of repairs as a consequence of blocked ducts. Also, it is far more preferable to keep water out of ducts than to have to remove it prior to grouting. Excess water dilutes grout and can lead to bleed and grout voids which, in turn, may facilitate corrosion. Filling grout voids after the grout has set, is difficult and may require special vacuum grouting - which is costly. A little prevention is worth far more than the cure!

3.5 Tendon Installation

3.5.1 Tendon Types

Main longitudinal, internal or external tendons set to a curved or draped profile are usually made up of multiple 12 or 15mm (0.5 or 0.6 in) diameter, seven-wire strands. The number of strands per tendon depends upon the range of anchor and wedge plate hardware available for that system.

Similar strands are used for transverse tendons in the deck slabs of precast or cast-in-place segments - but only three or four strands are laid side-by-side in a flattened oval duct draped to a very shallow profile. Occasionally, straight bar tendons may be used transversely.

Post-tensioning bars are most often used for temporary applications; erection of precast segments, securing erection equipment such as gantries and form travelers. Bars are more expensive than strands for a given post-tensioning force, primarily because of the cost of the anchor plates, nuts and couplers. Re-use is appropriate and economical for temporary work, providing that the stress does not exceed more than about 50% GUTS and the number of re-uses is limited normally to about ten; or as otherwise recommended by the manufacturer. For installation, post-tensioning bars are usually placed through straight ducts of sufficient diameter to provide adequate tolerance for construction (2.3.1.2).

3.5.2 Proving of Internal Post-Tensioning Ducts

Prior to installing internal tendons, it is recommended that ducts be proven to be clear of damage or obstructions by passing a suitable sized torpedo through the ducts. The torpedo should have the same cross sectional shape as the duct but 6mm (¼in) smaller all around than the clear, inside dimensions of the duct and should have rounded ends. For straight ducts the torpedo should be about 0.6M (2ft) long. For sharply curved ducts the length should be such that when both ends touch the outermost wall the torpedo is at least 6mm (¼in) clear of the inside wall; but it need not be longer than 0.6M (2ft). A duct should be satisfactory if the torpedo can be pulled easily through by hand without excessive effort or mechanical assistance.

For guidance, it is recommended that this test be performed on each individual tendon in a precast girder or similar component before it is released from the precast yard. For all cast-in-place construction with internal tendons, this test would be done on site. For internal tendons in precast segments, this test would be done on site after erection. Proving ducts with a torpedo is recommended for all internal longitudinal tendons over approximately 15M (50 feet) long and may be used, as necessary, for shorter tendons or as otherwise required by specific project documents. This check is not necessary for transverse tendons in slabs of precast segments when tendons are installed in the casting yard. It is not necessary for the short lengths of internal longitudinal tendons in precast segments while in storage.

3.5.3 Installation Methods

Post-tensioning strands may be pushed or pulled through ducts to make up a tendon. Pushing should be done with care using a protective plastic cap provided by the PT system supplier so that it does not get caught or damage the duct. Pushing single strands into a duct already containing many strands may become difficult as the duct is filled with more strands.

Sometimes it may be easier to pull the entire bundle through together using a special steel wire sock or other device securely attached to the end of the bundle (Figure 3.25). Welding strands together with a pulling eye is not recommended because the heat of welding alters the steel properties and reduces its strength even when a few feet are wasted.

For transverse post-tensioning in deck slabs, sometimes a Contractor may wish to place strands in ducts before concreting to provide extra rigidity. If this is done, the transverse strands should be checked to see that they can move in the ducts after casting in order to ensure that they are indeed free before they are stressed.

In any event, if strands are placed in ducts before casting concrete, the time for completion of stressing and grouting commences from the moment the tendons are placed in the duct.

Figure 3.25 - Steel wire sock for installing multi-strand tendon

3.5.4 Aggressive Environments

For aggressive environments, when ducts may be contaminated with chlorides, they may require flushing before installing tendons. Only clean water should be used for flushing. The ducts should be well drained. All water should be removed before grouting. If necessary, flushing water should be blown out of the ducts before installing tendons, using dry, oil-free compressed air.

3.5.5 Time to Grouting and Temporary Tendon Protection

The time between the first installation of the prestressing steel in the duct and the completion of the stressing and grouting operations should not exceed the recommendations of the AASHTO LRFD Construction Specifications.

Any light surface corrosion forming during this period of time should not be sufficient to reject the prestressing steel. However, unless approved by the Engineer, failure to grout tendons within the time limit might be sufficient reason to stop work until the concerns are resolved.

The use of water soluble oil to reduce friction for installation and stressing or for temporary corrosion protection of an installed tendon is not recommended as it has been shown to reduce bond. Furthermore, it can never be satisfactorily removed from the strands and ducts and any residual water in the ducts spoils the grout, leading to excessive bleed, grout voids and possible corrosion.

Ends of tendons should be protected by coverings until approval for cutting off the stressed strand tails after satisfactory stressing has been obtained from the CEI.

3.6 Jacks and Other Stressing Equipment

3.6.1 Types

3.6.1.1 Mono-Strand Jacks

Jacks for stressing single (mono) strands generally have two cylinders, one each side the strand, with a wedge device for gripping and pulling the strand (Figure 3.26).

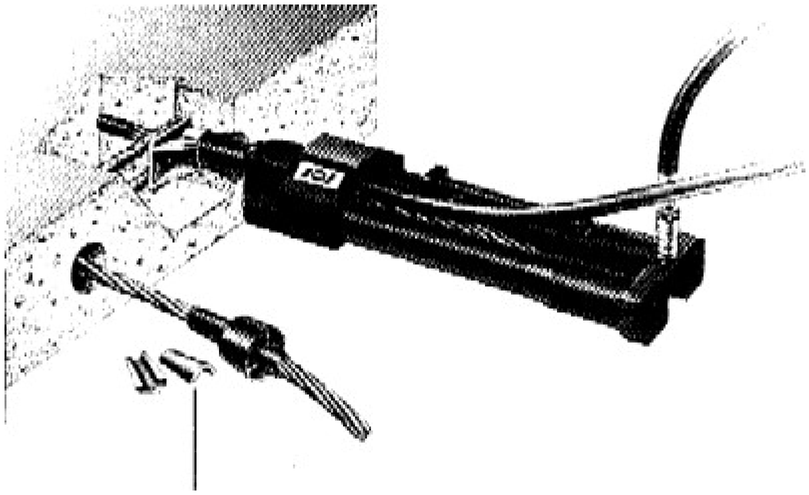


Figure 3.26 - Mono-Strand Jacks (Courtesy VSL Corporation)

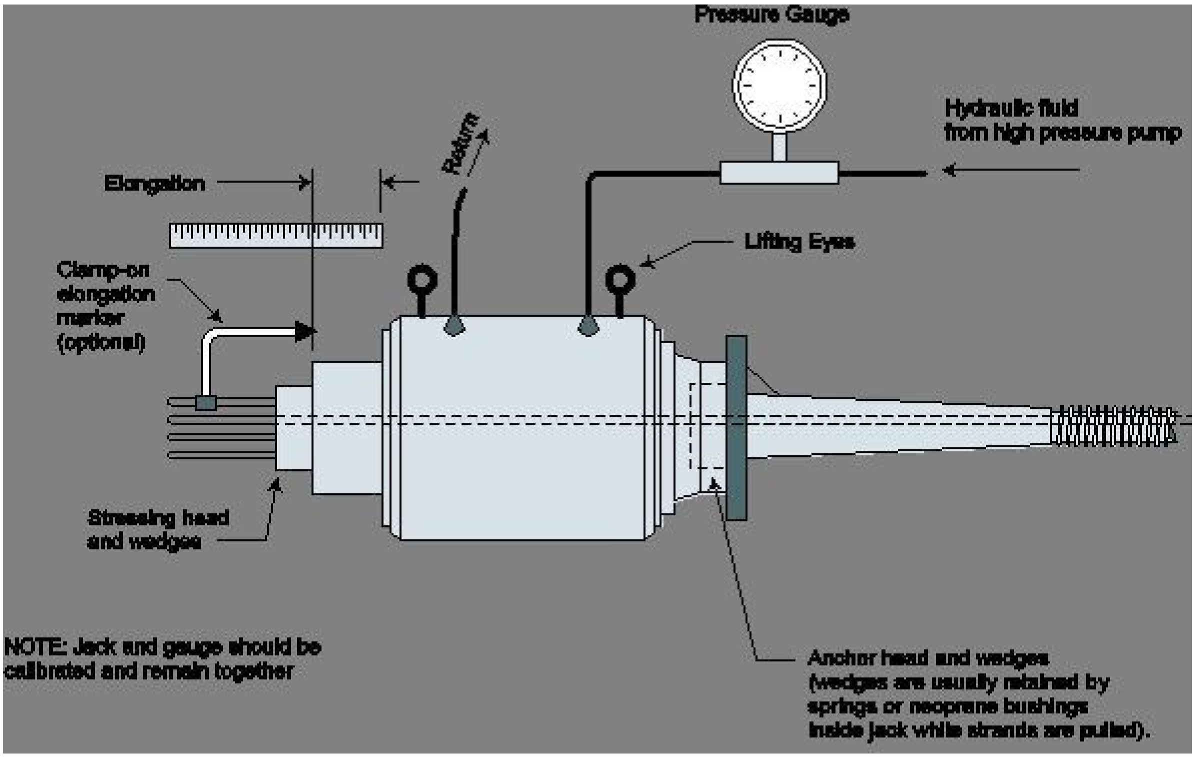
Mono-strand tendons are often used in buildings, where each tendon is a single strand in its own duct. In bridges, mono strand jacks are normally used to stress transverse tendons, usually comprising 3 or 4 strands, in deck slabs or similar applications. Also, mono-strands are often used for repair or rehabilitation.

Occasionally, longitudinal multi-strand tendons may be stressed one strand at a time, although this is usually only practical where each strand is clearly identifiable at each end and there is no risk of trapping an underlying strand in the process.

3.6.1.2 Multi-Strand Jacks

Multi-strand post-tensioning tendons are usually stressed as an entire group, using very large custom made jacks. This ensures that all strands are tensioned together and avoids the risk of trapping an individual strand. Stressing jacks are generally of the center-hole type - i.e. tendons pass through a hole in the middle and are attached at the rear of the jack (Figure 3.27).

Prestressing jacks must be very accurate - which is difficult to achieve. Stressing jacks have more wearing surface and packing than a conventional jack of the same capacity. This, and the necessity of a long jack stroke, increases the potential for variations in the accuracy of the applied force. Other factors that affect the accuracy and efficiency of stressing jacks are: use of dirty oil, exposure of the system to dust or grit, eccentric loading, type of packing, ram position, oil temperature, hydraulic valves, ram and packing maintenance, and readout equipment.



NOTE: Jack and gauge should be calibrated and remain together

Figure 3.27 - Typical multi-strand, center hole, stressing jack

Another effect is hysteresis. Hysteresis is an energy loss due to a hydraulic pressure change inside the jack, causing inaccurate load values when the ram pressure is static or decreasing. An increase of hydraulic pressure also causes an energy loss, but this loss is taken care of by calibrating the jack and pressure gauge with a load cell during this increase of pressure.

The jacking system should be fitted with a pressure gauge which registers the pressure of the hydraulic jacking fluid. The pressure gauge and jack must be calibrated together and remain together as a unit throughout all stressing operations. Pressure gauges and jacks should not be interchanged. If they are, then the new system must be recalibrated before use in production stressing.

Pumps for hydraulic fluid delivery must be kept in good working order. Breakdowns in the middle of the stressing operation are undesirable.

3.6.1.3 Bar Jacks

Bar jacks have a central hole through which the bar passes and is secured by a nut at the rear of the jack (Figure 3.28). Most jacks have an enlarged nose to accommodate a bar-coupler.

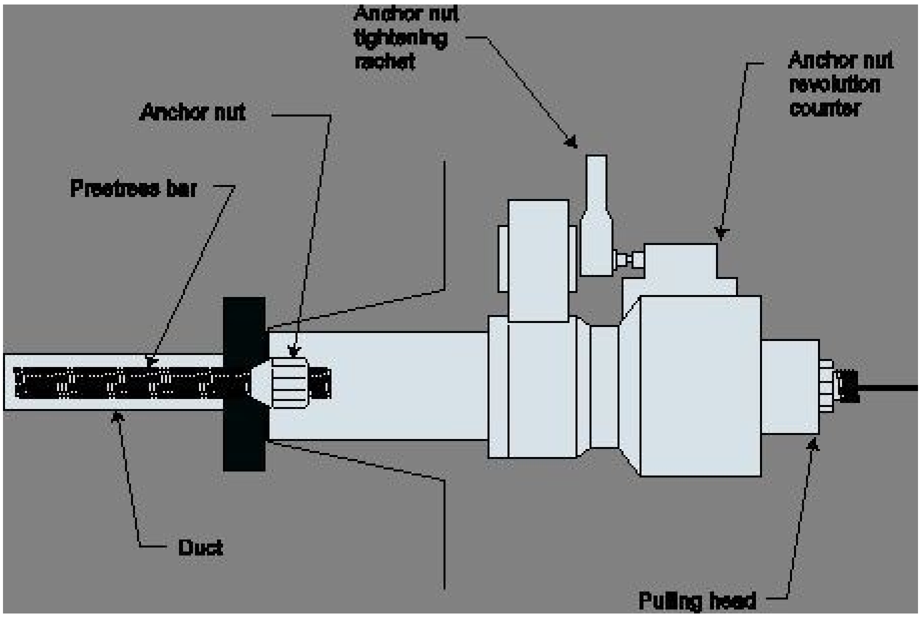


Figure 3.28 - Prestressing Bar Jack

Also, bar jacks have a hand or mechanical ratchet to rotate and tighten the anchor nut against the anchor plate as the bar elongates under load. With care, by tightening the anchor nut, anchor set or seating loss can be minimized or eliminated.

3.6.2 Calibration

Jacks should be calibrated every six months as a minimum.

3.6.2.1 Jack and Gauge

Calibration is most important. This is a process where the load delivered by the jack to a tendon is measured by a precise load cell or other equipment. The readings of the jack's pressure gauge are noted against the readings of the load cell through the entire jacking range to create a chart of pressure gauge reading versus actual load recorded by the load cell. The chart only applies to this particular jack and gauge combination - it does not apply to any other.

When used for stressing, the actual force in the tendon is easily found from the pressure gauge and calibration chart. In general stressing jacks are about ninety-five percent efficient; but actual efficiency will vary depending on the age and condition of the jack. Any calibration chart which shows jacking forces much greater than ninety-five percent of pressure multiplied by piston area should be questioned.

With use, a jack and gauge system can drift out of calibration. So, on large projects, a calibration load cell is normally kept on site and the jack and gauge are periodically checked. On small projects, the jack and gauge system should be calibrated immediately prior to use. This is often done by the supplier of the system or by a local, approved laboratory.

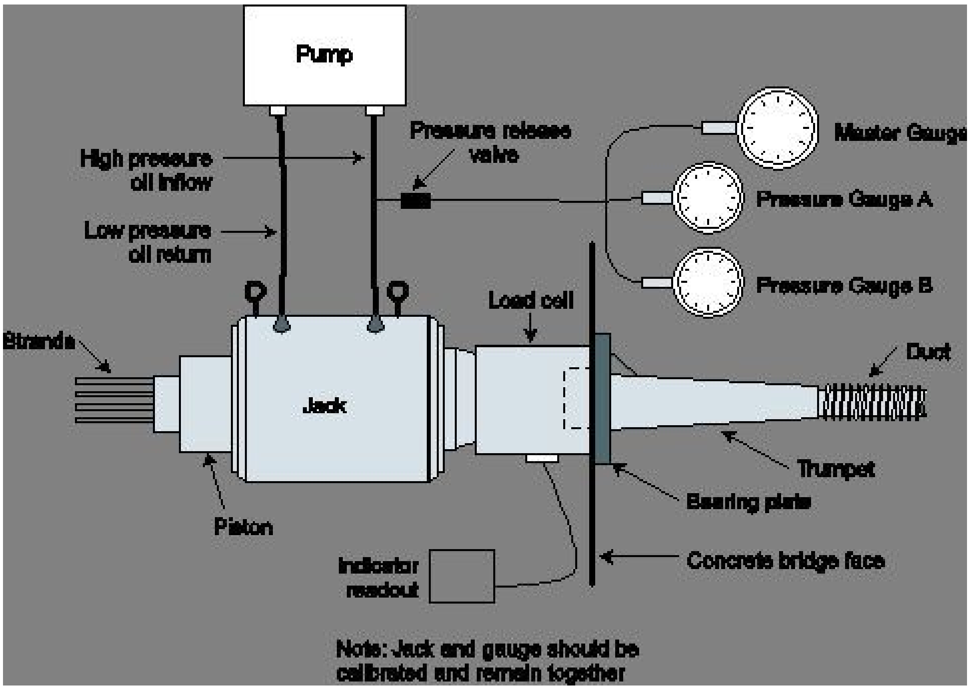


Figure 3.29 - Jack Calibration

Figure 3.29 shows the set-up for jack calibration. In addition to the normal set-up for stressing, two instruments are added: the load cell between the jack and the anchorage and a master gauge attached to the pressure gauge to be calibrated. The load cell is normally placed in front of the jack, as shown. The load cell allows an accurate readout of the force applied to the prestressing tendon. Load cells are laboratory instruments which, in turn, are calibrated with a "National Bureau of Standards" load cell.

3.6.2.2 Master Gauge

The master gauge measures hydraulic pressures accurately. The load cell operates on the principle that changing pressure results in a corresponding change in electrical resistance. The readouts are made with a so-called Transducer Strain Indicator.

Gauge readings should not be taken while the ram is retracting or in a static condition as hysteresis will likely result in erroneous values. The calibration curves and master gauge readings are only valid when the ram is extending.

If there is any indication of damage to the gauge, the stressing system should be checked with the master gauge. For this reason, the master gauge should be kept locked away in a safe place so that it is always in good working order. If there is more than 2% difference between the master gauge and the calibration chart, the jack and gauge should be recalibrated. Usually the stressing Contractor has the jacks calibrated with the master gauge and at least one other gauge (B) as a back-up.

3.6.2.3 Calibration Curve

A calibration curve relates the pressure recorded by the jack's own gauge to the actual force delivered by the jack (Figure 3.30). The curve is established by the above calibration process. It can be found for the jack's gauge and the master gauge. The jack and gauge must remain together as a unit at all times while in use in order to avoid mix-ups and incorrect results.

Periodically during use, the jack and gauge should be checked by inserting the master gauge. Significant variation from the calibration curve would be reason to examine the jack system.

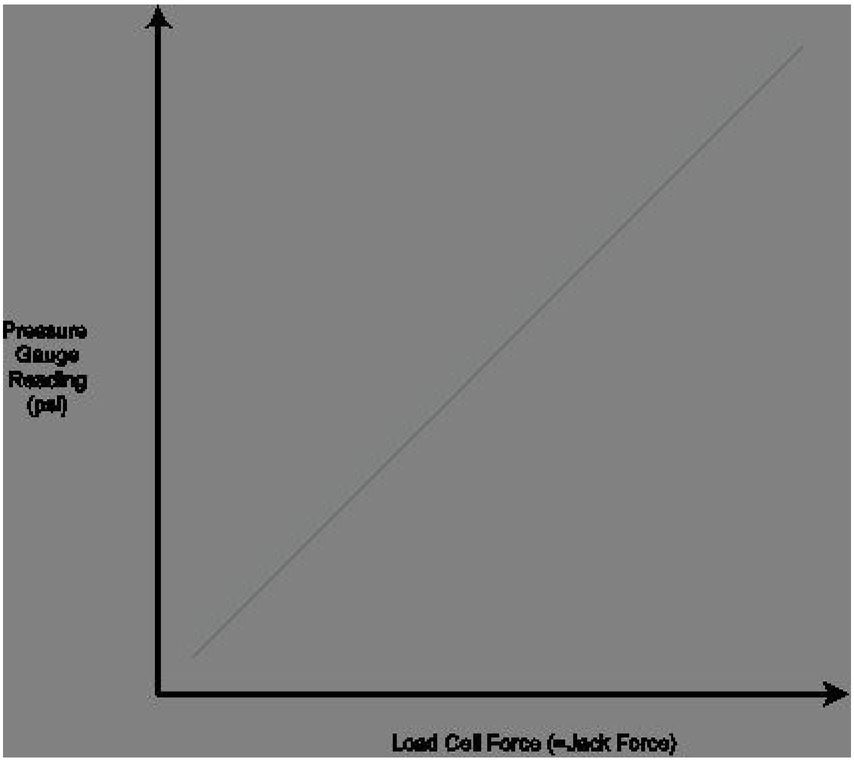


Figure 3.30 - Calibration Chart for Pressure Gauge and Jack Force

3.6.2.4 Jack Repair

If a jack needs repair, then the repaired jack and gauge should be re-calibrated. (Repair to pressure hoses alone would not be reason for recalibration.)

3.7 Jacking Methods

3.7.1 Single (Mono) Strand Stressing

Single strand stressing using a monostrand jack is normal practice for transverse tendons in deck slabs (Appendix C) where each strand lies side by side in a flat-oval duct where it cannot interfere with or trap another strand. Similar applications might include relatively short longitudinal strand tendons in precast planks or solid or voided slabs.

Single strand stressing can be used on multi-strand longitudinal tendons only if they are straight or curve only in one direction so that the strands on the inside of the curve can be stressed before those on the outside to avoid trapping. For this reason, single strand stressing is not suitable for multi-strand tendons of reverse curvature.

When single strand stressing is used for a small section girder, allowance should be made for the elastic shortening loss induced in the earlier stressed strands by the stressing of subsequent ones. This should be taken into account in the design or construction engineering of the component.

Mono-strand stressing techniques are available for greased and sheathed strands for cable-stays and similar, external tendon, applications for repair or rehabilitation.

The sequence in which tendons are stressed and the ends from which they are stressed should be clearly shown on the Contract Plans or approved Shop Drawings, and must be followed.

3.7.1.1 Single Strand, Single End and Alternate End Stressing

When single mono strand stressing involves short tendons, it is usually only necessary to stress from one end because friction loss is small (although care is needed to make sure wedge set loss is not excessive on a short tendon).

In order to maintain relatively even dispersal of post-tensioning, transverse tendons in deck slabs should be stressed from alternate ends - i.e. stress all the strands of one tendon from one side of the bridge and switch to the opposite side for the next tendon - and so on. This may be referred to as "Alternate End Stressing". It should only be necessary in special cases (as determined by the Designer) to stress the strands of one tendon from alternating ends.

3.7.1.2 Single Strand, Two End Stressing

Two end stressing means stressing the same strand from both ends. This may be done sequentially, from one end at a time or simultaneously using two jacks. However, stressing from both ends would normally only be needed for long tendons where friction loss is significant. Stressing from the second end should not be done if the calculated elongation is less that the length of the wedge grip. Re-gripping in a portion of the old grip length should be avoided.

3.7.2. Multi-Strand

Multi-strand tendons are the most frequent choice for main longitudinal tendons in bridges. All the strands of one tendon are tensioned together using a multi-strand jack. The sequence in which tendons are stressed and the ends from which they are stressed should be clearly shown on the Contract Plans or approved Shop Drawings and must be followed.

3.7.2.1 Multi-Strand, Single End and Alternate End Stressing

When a multi-strand tendon is stressed from one end it is often referred to as "single or one end stressing" to distinguish it from tendons stressed from both ends. However, with a number of similar and often symmetrical tendons in a superstructure, that need only be stressed from one end, it is desirable to keep the overall post-tensioning effect as even as possible by stressing similar tendons from alternate ends of the structure. When this is done it is often referred to as "alternate end stressing" and it means that tendons are stressed from one end only, but from opposite, alternate, ends of the bridge.

The location of the jack is switched from one end of the structure to the other in such a way that an equal number of tendons are stressed at each end (Figure 3.31). If stressing starts with T1 on the east side of the structure, tendons T2 and T3 are stressed from the west side and T4 again from the east side.

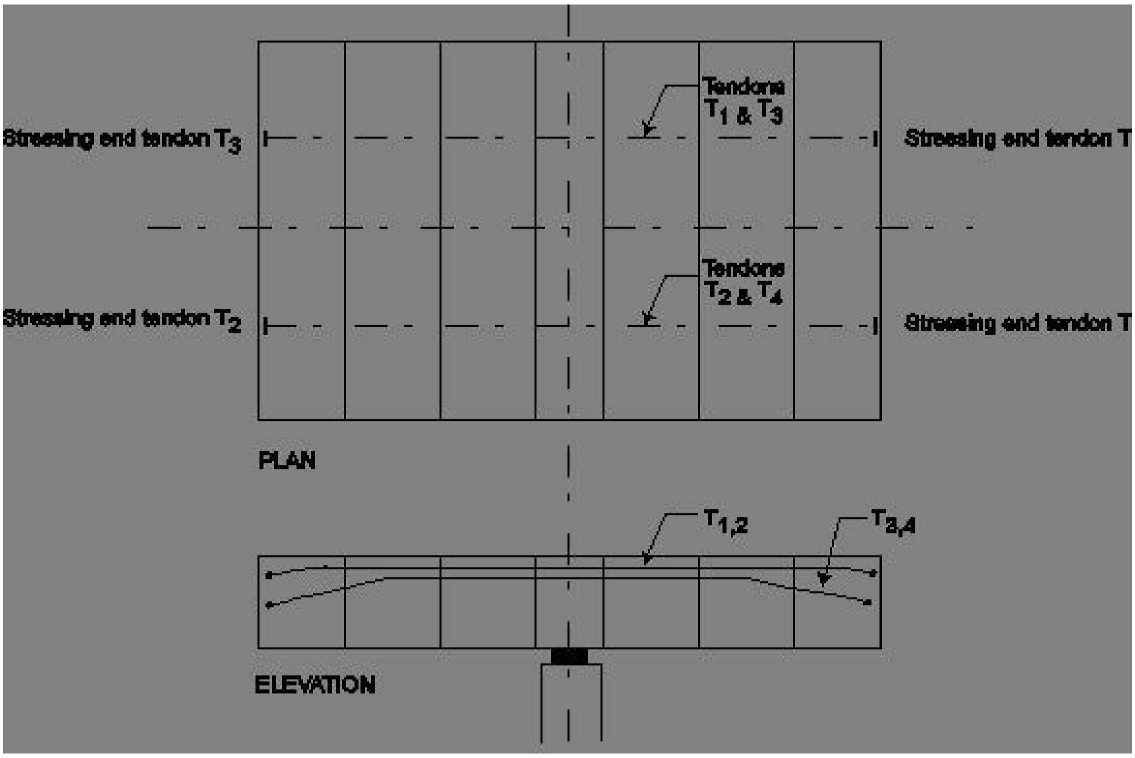


Figure 3.31 - Alternate end stressing

Alternate end stressing results in a more or less even distribution over the section. Since the tendons are stressed from one end only the forces at the live ends will be greater than the forces at the dead ends. Each individual tendon causes a non-symmetrical stress distribution.

By alternating the stressing ends the overall effect is more or less symmetrical. Since the design of the structure is usually based on a relatively even distribution per the alternate end stressing sequence, it is very important to adhere to the correct, specified sequence.

3.7.2.2 Multi-Strand, Two-End Stressing

When the tendons are very long, losses over the length of the tendon due to friction and wobble become large. Stressing the tendon from the second end results in a higher force in the tendon than if only stressed from one end. Also, for symmetrical tendons two-end stressing becomes effective when the effect of anchor set at the jacking end affects less than half of the tendon (Figure 3.32). Stressing from the second end should not be done if the calculated elongation is less that the length of the wedge grip. Re-gripping in a portion of the old grip length should be avoided.

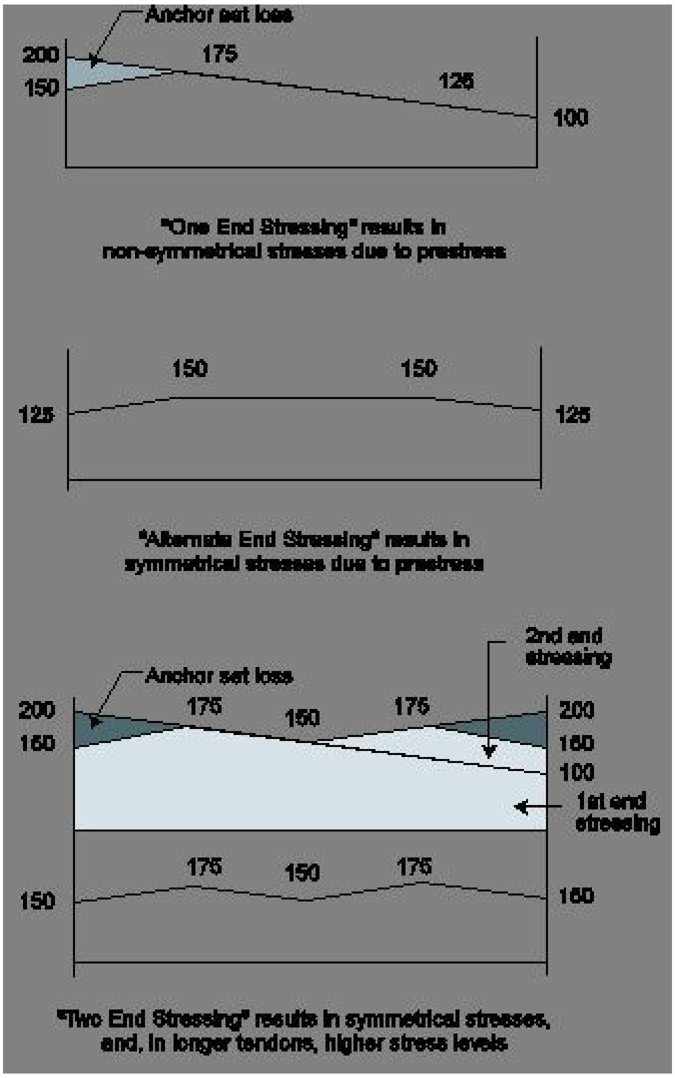


Figure 3.32 - Stresses along tendon for different modes of stressing

There are two ways of stressing the tendon. The first and most common method is to start stressing from one end. The elongation will be rather large and the tendon will have to be anchored and probably re-gripped several times. The number of re-grips will depend on the stroke of the jack. Elongations are roughly in the 178 to 203mm (7 to 8-in) range for every 30M (100 ft) of tendon. Using a jack with a 250mm (10-in) stroke and tendon approximately 150M (500ft) long tendon, 4 re-grips will be needed.

When the tendon has been stressed to the final force at the first end the wedges are seated and the stressing operation moves to the other end. At this second end the tendon will already have a considerable force (there is no slack to be pulled out of the tendon and elongation measurements can start immediately). Elongations at this end will be relatively small and re-gripping of the jack is not normally necessary. The total elongation for the tendon will be the summation of the elongations measured at each end. Re-gripping is a source of error in the measurement of elongations. Care should be taken that no reference marks are lost during the re-gripping.

The second method involves a simultaneous jacking operation at both ends using two jacks. Each jack pulls approximately half of the total elongation. There is no reason why these elongations should be exactly the same. The advantage for the Contractor should be that the stressing operation and movement of equipment from one location to another can proceed somewhat faster since this method involved less individual re-gripping. Two sets of equipment are required and some reliable means of communication to synchronize operations.

3.7.3 Bar Tendons

Bar tendons have either a coarse or fine thread and are anchored by a nut bearing against an anchor plate. Bars are stressed individually using a special jack (Figure 3.28).

Curved bar tendons are rarely used nowadays; the vast majority of bar tendons are straight. With good clearance around the bars, there is no friction loss. Also, when the nut is gradually tightened using the ratchet on the jack as load increases, there is little or no seating loss. Consequently, the force is the same throughout and there is no need to stress from both or alternating ends.

The sequence in which PT bars are stressed should be clearly shown on the Contract Plans or approved Shop Drawings. For example, many PT bars are used for erecting and closing epoxy joints in precast segmental construction. It is important to maintain as uniform pressure as possible in order to evenly compress the soft epoxy. This is achieved by stressing the bars in a certain specified sequence. Similar situations apply to vertical PT bars in pier columns. Consequently, the sequence should be followed.

3.8 Stressing Operations

3.8.1 Personnel and Safety

Prestressing tendons are the backbone of the structure. When properly stressed, they will prevent the structure from cracking and deteriorating. But,a badly stressed tendon looks exactly like a properly stressed tendon. Therefore, the only way to ensure proper stressing is to have an experienced, trained crew (Appendix B) and an inspector present during all stressing operations.

Stressing should be considered a basically unsafe operation. People operating the equipment and taking measurements should never stand behind a live jack. This is also true at the dead-end of the strand: never stand behind the anchor of a tendon being stressed. Although it does not happen often, tendons do break, wedges do let go and large forces are released in a split second, making jacks jump and propelling tendons out of an anchorage. In order to make everybody on the project aware of the fact that there is a tendon being stressed, a warning system should be in place such as flashing lights or red flags.

3.8.2 Jacking Force

The force required in each tendon is determined by the Designer and is given on the approved shop drawings or job stressing manual. Also, the corresponding elongations are pre-determined taking into account all losses due to curvature friction, wobble, wedge set, and friction within the anchor and jack, as necessary. For post-tensioning, measurement of elongations serves as a check of the anticipated jacking force primarily given by the gauge pressure and calibration chart.

The stressing operation should constantly be monitored by an inspector. There are two basic pieces of information that need to be recorded: tendon elongations and gauge pressures. Both will give an indication whether the tendon is stressed to the force required. The gauge pressure is a direct measurement of the force at the jack and the elongation will give an indication how the remainder of the tendon is being stressed. Normally the tendon will be stressed to a predetermined gauge pressure, representing a certain force in the tendon at the stressing end. The elongation measured at this point is compared to the theoretically determined elongation.

3.8.3 Measuring Elongations on Strand Tendons

When stressing a tendon a certain portion of jack extension will be needed to remove the slack. This gives a false initial elongation that should not be part of the real elongation measurements. For this reason, the first step is to stress the tendon an initial force of approximately 20% of the final force to remove the slack. From this point up to 100% of the required load, the extension of the jack will cause pure elongations of the tendon. At the end of the operation, a correction can be made for the unmeasured portion of the elongation by straight extrapolation.

The accuracy of the determination of the elongation obtained during the first step, i.e. tensioning up to 20% of the jacking force, can sometimes be improved by recording elongations at intermediate gauge readings of 40%, 60% and 80% and plotting results on a graph. Ideally, the graph should be a straight line.

Intermediate elongations must be recorded if a long tendon has to be stressed using two or more pulls on the jack when the required elongation is greater then the available stroke.

For short, mono or multi-strand tendons it may suffice to check the elongation for the stressing range between 20% and 100% load against the calculated value for this range. Short tendons are those generally less than about 30M (100 feet) long where the expected elongation is only about 0.2M (8 inches) or less and is easily made with a single, steady and continuous stroke of the jack. Short tendons include, for example, transverse tendons in deck slabs.

Elongation may be measured by the extension of the cylinder beyond the barrel of the jack. However, this is acceptable only if the wedge pull-in of the internal wedges that grip the strand inside the jack is reliably known; it is deducted from the measured extension on the cylinder to give the actual strand elongation. This method is often preferred for convenience.

Alternatively, measurement of elongations may be made to a point directly by adding an attachment to one of the strand tails and measuring between the tip of the attachment and the (immovable) barrel of the jack. In fact, the difference between this measurement and that solely of the cylinder extension is the pull-in of the internal jack wedges.

Alternatively, elongation can be measured directly from the face of the concrete to a mark on the strand tails. At least two randomly selected strands are marked. The mark can be a scribed mark or saw cut on the strand tail beyond the back of the jack or it can be made with tape or spray paint and pencil. The mark is placed after 20% of the jacking force has been applied. The distance of the mark to a fixed point on the concrete face or on the immovable barrel of the jack is recorded. As the jack is pumped out, this distance increases. Elongation measurements are made only on one of the marked strands. The other marked strand is there just in case the strand being measured should slip.

With any multi-strand stressing operation, it is good practice to mark several strand tails (at 20% load) at the same location using spray paint and pencil or tape to give a visible assurance that the strands are elongating by the same amount; any slip is easily noticed.

When stressing reaches full load, providing that the elongation is within the required tolerance of that anticipated, the jack is released and the tendon is anchored off by the permanent wedges. Wedge pull-in must be recorded and deducted from the elongation at full load to give the final actual elongation at this end of the tendon.

For small cross section members, such as I-girders, proper account should be taken to compensate for elastic shortening of the concrete when measuring elongations.

3.8.4 Measuring Elongations on PT Bars

Temporary bar tendons for erection purposes are usually short (i.e. from about 3 to 6M (10 to 20 ft) long). Elongations are small and are not usually measured for temporary applications; bars are jacked to load given by jacks pressure gauge.

For permanent PT bars, elongations should be checked as secondary verification of force. The elongation should be measured from a fixed point on the face of the concrete to a mark on the bar beyond the end of the jack. The slack, as in couplers, should be removed by applying 20% of the load. The elongation for the range between 20% and 100% required load should be checked against that calculated for this range.

For small cross section members, such as I-girders, proper account should be taken to compensate for elastic shortening of the concrete when measuring elongations.

3.8.5 Field Variables

3.8.5.1 Friction

Friction between the strands and ducts and within anchors and jacks reduces the effective force in the tendon. The main sources of friction are:

- Friction between the tendon and duct due to curvature of the tendon profile("mq").
- Friction between the tendon and duct due to unanticipated wobble ("kl").
- Friction in the anchorage as strands flare to pass through the wedge-plate (%).
- Friction within the jack itself. (This may be given as a percentage (%) by the post-tensioning supplier or it may be eliminated by use of a calibration curve of gauge pressure verses delivered jacking force).

An allowance for each effect is made by the Designer or the Contractor's Engineer and the required jacking force and corresponding tendon elongation is given on the plans, shop drawings or stressing manual.

3.8.5.2 Anchor Set or Wedge Set

When a strand tendon has been jacked to the required force and the jack is released, the wedges are drawn into the wedge plate until they bite and secure the strand. Typically the amount of wedge set or "draw-in" is about 10mm (3/8in) (Figure 3.33).

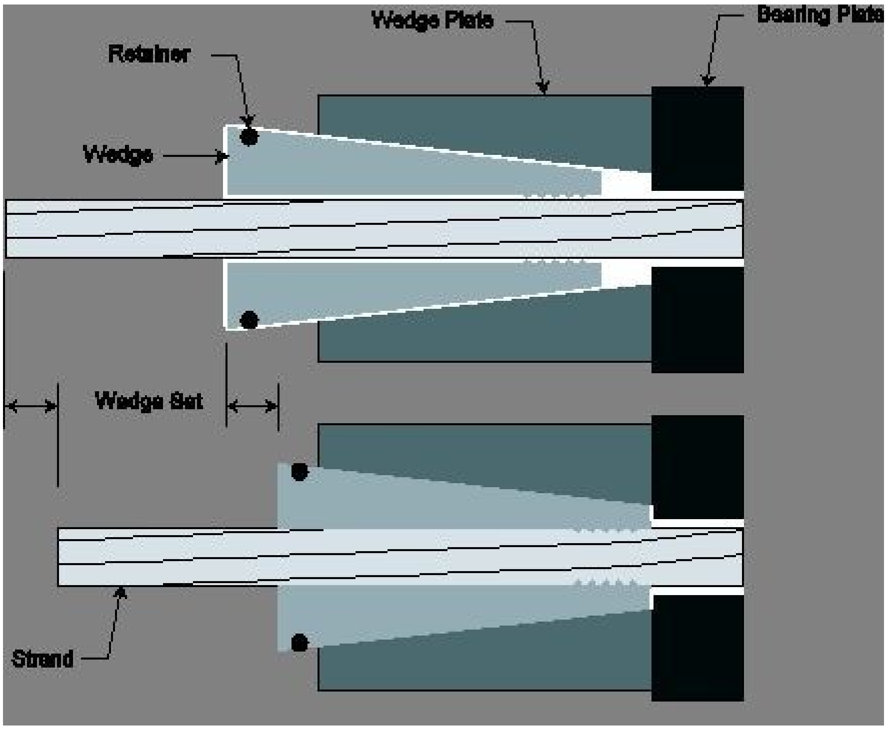


Figure 3.33 - Anchor Set or Wedge Set

Some jacks have devices from power-seating the wedges prior to releasing the force. This can offset most of the wedge seating loss. In addition to the wedge seating, there is an elastic deformation of the wedge plate - it is relatively small compared to the wedge seating. Together, these effects may be referred to as "anchor set" or "wedge set". It represents the amount that a point on the strand just inside the anchor moves as load transfers from the jack to the strands.

Wedge set is measured in the field using the same reference marks on the strands as used for elongations. It is the difference between the elongation before and after release of the jack.

3.8.5.3 Strand Slip

Occasionally during stressing strands may slip at the wedges. This might happen if the size of the strands and wedges are at opposite ends of their manufactured tolerance range.

When stressing the crew and inspector should make sure that no strands slip. All strands in the tendon should be marked at both ends so that a slipped strand will show up immediately. One way to do this is to cut the strands off evenly at both ends after the jack has been attached and pressurized. The cut should be made at some distance from a dead end wedge plate and beyond the rear of the stressing jack(s) leaving a sufficient length projecting in case it is necessary to re-grip and re-stress. Another method is to mark all strands with spray paint. A slipped strand will show up promptly by lagging behind the other strands. (It is not possible, nor is it necessary except in very unusual circumstances, to identify which strand is which at both ends of the tendon).

3.8.5.4 Re-Gripping of Strand by Wedges

In multi-stage stressing of a long tendon that requires re-gripping, it is important to makes sure that intermediate re-gripping does not take place at a location that has already been gripped by wedges - or else slip or breakage could occur.

3.8.6 Final Force

The final force in the tendon is the jacking force minus all effects due to various losses described above. If after release of the jack, there is some doubt about the adequacy of the force a "lift-off" test may be necessary (see 3.8.8).

In the field, during stressing operations, it is only possible to monitor the jacking force given by the gauge pressure and calibration chart and to measure the elongation and wedge seating. These are the essential observations needed to ensure that the tendon has the required final force. They should be properly recorded in a stressing report. An example of a Stressing Report is given in Tables 3.3 (a) and (b).

Tendon force is primarily determined by the jack gauge pressure and calibration chart. Measured elongations are a secondary check of tendon force and should agree within 5% of calculated values for tendons over 15M (50 feet) long or 7% for tendons less than this (AASHTO LRFD Construction Specifications 10.10.1.4). Some project specifications may have different percentages for agreement for both long and short tendons.

3.8.7 Strand End Cut-Off

The ends of the strands should only be cut off if the jacking forces and elongations are satisfactory. If there is any doubt that might require verification by a lift-off test or additional jacking, strands should not be cut. Preferably, strands should be trimmed as soon as possible, so that permanent grout caps can be placed over the wedge plate to seal the tendon until grouting.

Strands should be cut off at the wedges leaving approximately 12 to 20mm (½" to ¾") of strand projecting but no greater than that which can be accommodated by any permanent non-metallic grout cap supplied for installation with the post-tensioning system. Strands should be cut only with an abrasive cutting tool. Under no circumstances should flame cutting be used as the heat can soften the strands and wedges and lead to loss of strands. Recently, plasma cutters have become available; their use should only be with strict inspection and approval of the Engineer.

After strand tails have been cut-off, the ends of the tendon should be temporarily protected in an approved manner until the tendon has been grouted. Preferably, a non-metallic (plastic) grout cap should be placed over the strands and wedges.

3.8.8 Lift-Off

Occasionally, after release of the jacking force, if there is some doubt of the adequacy of the force a "lift-off" test may be necessary. The jack remains in place or is re-installed and gradually taken up to load. The strands are marked and the position of the mark from the face of the anchor plate is measured very carefully. If this mark is beyond the end of the jack, then as the jack load increases, it will move only by the amount of elongation on that part of the strand passing though the jack. Since this is very little amount it may be immeasurable.

When the load reaches and passes that in the tendon, the tendon itself begins to elongate over its full length (less the effects of friction). This elongation should be noticeable by measuring the marks. The gauge should begin to register a higher pressure than that at which the tendon was first released. Also at this point, the wedges should begin to move from the wedge plate. This is the point of "lift-off" and should verify the force in the tendon at the jack.

A caution: if the load is significantly low then jacking to the required load may proceed providing that the previous point of the wedge grips is elongated clear past the wedges so they bite onto fresh strand. If not, there is a risk that the wedges may not properly re-grip. Hence, lift-off tests should be performed only when necessary and not as a matter of routine.

3.9 Stressing Records

All information relating to the stressing of a tendon should be recorded. The stressing reports are very important. They will be invaluable when problems occur during the stressing operation.

The following information should be included in the report:

- Tendon identification e.g. tendon number, girder/web number, span/unit number.
- Date and time when the tendon was stressed.
- Information on the strand used to make the tendon - such as the coil pack and heat number for the strands.
- The jack and gauge identification numbers.
- The required elongation and jack force or gauge pressure.
- The anchor set at the live end as well as at the dead end.
- The stressing end(s) for the tendon.
- The pressure gauge readings at which elongation measurements are made. Important are the initial and the final readings -intermediate readings should be carefully noted.
- Any comments about events that occurred during stressing operation - such as wire breakages, slipped strands, popping noises etc.
- The name of the inspector and the stressing crew foreman.

A sample stressing report is shown in Tables 3.3 (a) and (b) (at the end of this Chapter) for Example 1, the four-span I girder of Figures 3.2 and 3.3. For clarity, this is shown in customary U.S. units at this time. The format and type of information on a report may be adapted for a project, as necessary.

3.10 Stressing Problems and Solutions

During stressing operations several things can go wrong: the following addresses some of the more common problems and their solutions.

3.10.1 Strand Slip

Slip of a strand can occur during the stressing operation and while anchoring the tendon. The reason is normally a defective wedge. This may be caused by a rusty surface on the outside of the wedge or the inside of the chuck, preventing the wedge from having a firm grip on the strand. Worn out teeth on the wedges inside the jack can also be a reason. In most cases, slip can be prevented by using properly maintained chucks and wedges.

Slip during stressing should reveal itself at marks made on the strand tails for this purpose. If slip is significant, (say, more than about an inch) it should be taken into account when stressing the remainder of the tendon. The slipped strands are under a lower stress. This will result in a lower overall force in the tendon for the required elongation. However, in order not to overstress other strands that do not slip, the target gauge pressure should be reduced in proportion to the number of slipped strands and amount of slip on each.

For example, if one strand out of 12 slips completely, the target gauge pressure should be reduced by one twelfth while the tendon is stressed to the required original elongation.

For example, if there are 12 strands and the target elongation is 152mm (6in) and slip of 50mm (2 in) occurs on one strand and 75mm (3 in) on another, the target gauge pressure should be reduced by (2+3) / (6*12). (If this example actually occurred on site, then operations and equipment should be examined carefully and appropriate action taken to rectify the problem.)

In order to attain the required final force in a tendon with slipped strands, the slipped strands may be stressed individually to their final elongation and force level using a single (mono) strand jack after stressing the remainder. However, care should be taken because the slipped strands may be trapped and, although they probably can be stressed to the required strand force, it is unlikely that the elongation will be attained. The Engineer should be present when work on a tendon with slipped strands is in progress.

If slip occurs upon release of the jack after otherwise stressing the tendon to full load and elongation without mishap, then it can be corrected by stressing the individual slipped strand(s) back to the original elongation using a single (mono) strand jack. Again the Engineer should be present.

The stressing of individual strands needs to be done immediately and should not be postponed. There is always the risk that a zealous worker will cut off strand tails before it is carried out. If and when this happens, the whole tendon needs to be removed and replaced.

3.10.2 Wire Breaks

Sometimes a wire will break in a tendon. If only one or two wires break, it may be a situation that of relatively little concern. For instance, when one wire breaks only 1/7 th of a strand's capacity has been lost. On a multi-strand tendon this will be much smaller proportion. A wire break is normally easily recognized by a sharp popping noise. Very often wire breaks will be within the anchor flare cone, possibly at the back of the wedge plate. It may be possible to see these using a borescope or similar visual probe. Most specifications allow up to 2% of the wires to be broken. However, persistent wire breakage should be investigated and action taken to change procedures or equipment to avoid or significantly lessen the problem.

When breakage becomes excessive, it reaches a point where the required force in the tendon is out of tolerance. In such cases, individual strands or whole tendons need to be replaced.

The cause of wire breakage should always be determined. Some possible causes are: overstressing, poor strand, bad wedges, or high friction points in the duct. Overstressing and high friction points show up when the stressing records are carefully examined. Sometimes strands and wedges may simply be at opposite ends of their respective allowable size tolerance ranges and the problem can be easily fixed by using different pieces.

3.10.3 Elongation Problems

Not reaching the required elongation can have several causes. One of the main reasons is a less than perfect tendon alignment. Sudden kinks in the alignment will increase friction loss considerably and consequently reduce elongation.

3.10.3.1 Too small elongation at jacking end under full load

Too small elongation may occur due to a kink close to the stressing anchor; the jack may reach full load, but the elongation will be very small. When this happens, the required elongation may possibly be achieved by stressing the tendon from the other end. However, this will not be feasible if low elongation is due to duct misalignment over the whole length of the tendon.

3.10.3.2 Low elongation for whole tendon

When low elongation is due to duct misalignments occur over the whole length of the tendon, stressing from the other end may not be enough to attain elongation. Consideration may be given to lubricating the tendon with water soluble oil or with graphite powder. This can reduce friction and result in better elongations. After a tendon has been successfully stressed, water soluble oil should be thoroughly removed by flushing. Flushing water should be thoroughly drained and blown from the ducts. Graphite powder may remain in the duct and is, therefore, generally preferred by many Contractors.

3.10.3.3 Elongation greater than tolerance

An elongation can be more than expected. This may be because of less friction than anticipated or because of slip of strands and wedges that went unnoticed. The wedges should be examined at both ends. It is for this reason that marks should always be made on strand tails at both ends the tendon. If there is no wedge slip and tendons persistently give an elongation greater than expected, the stressing calculations should be examined and appropriate adjustments made.

3.10.3.4 Low stressing force

It would be very unusual to not to be able to stress a tendon to a required jacking force; more often a problem is revealed by lack of elongation, not force. If force cannot be attained, the system should be checked. The possibility of increasing the jacking force may be considered. However, it should be checked by calculations using a higher wobble and friction coefficient to make sure that the stress in the tendon after anchor set does not exceed allowable stresses.

3.10.3.5 Overall Tolerance on a Group of Tendons

If none of the above lead to a satisfactory solution, it is possible to consider a problematic tendon as part of a whole tendon group - for example, one tendon out of perhaps sixteen to twenty in a cantilever, or similar. A tolerance for the whole group should be given in specifications or project special provisions. If all other tendons have a good stressing record, one poorly stressed tendon ought not to influence the group tolerance too adversely.

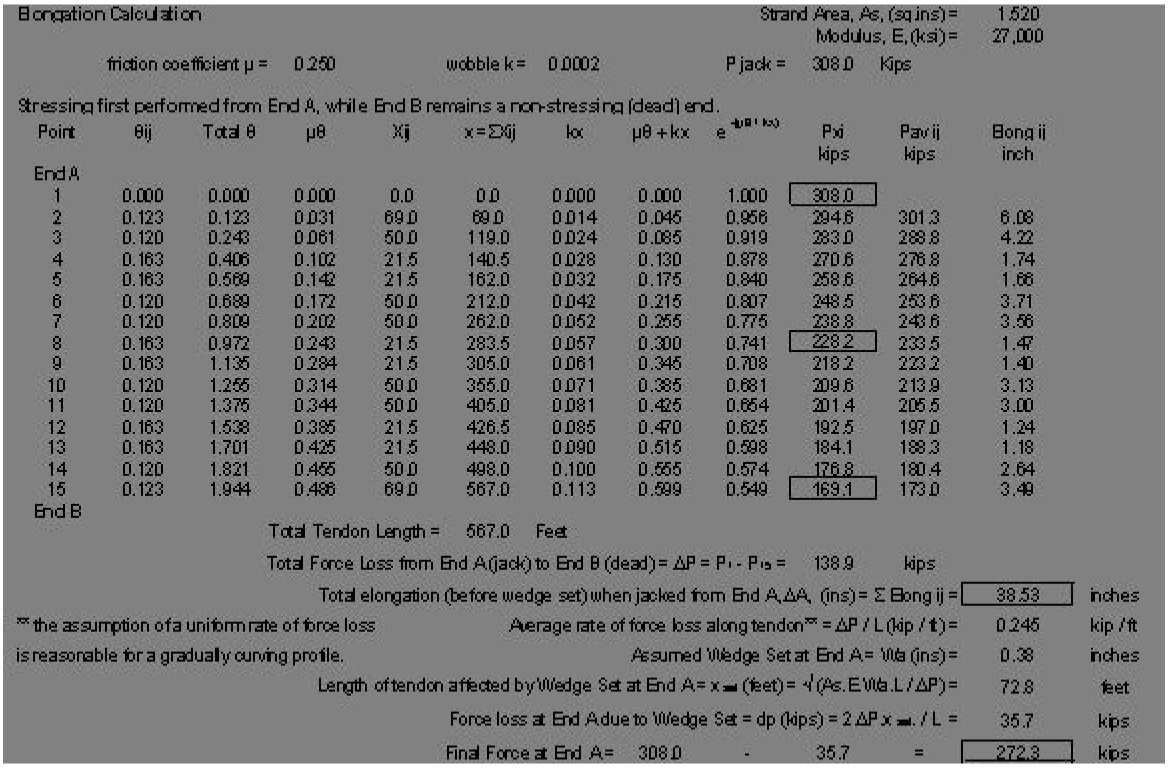
To make up for a loss of force in one tendon a compensating increase in force in other tendons may be considered, if there is sufficient reserve holes in the wedge plates to accommodate additional strands. Alternatively, if the shortfall is significant, it may be necessary to introduce or install additional tendons through provisions made on the plans or shop drawings.

3.10.4 Breaking Wedges

Sometimes wedges break. This causes the loss of the whole strand. It falls under the category of slipped strands and should be treated as such. When a few wedges break on the same tendon, all wedges should be considered potentially defective. The whole batch of wedges should be examined and, if necessary, replaced.

Very often wedges show radical cracks in their visible ends after seating. Experience shows that this is usually a localized cracking of the annular lip containing the retainer ring. Providing the strand has not slipped and providing this type of crack does not extend into the barrel of the wedge, then it is not of any major concern.

Repeated slippage problems and large cracks in the gripping nose of wedges are cause for concern and should be remedied.



Elongation Calculation

Strand Area, As, (sq.ins) = 1.520
Modulus, E, (ksi) = 27,000

friction coefficient μ = 0.250   wobble k = 0.0002   P jack = 308.0 Kips

Stressing first performed from End A, while End B remains a non-stressing (dead) end.

Point	θij	Total θ	μθ	Xij	x = ΣXij	kx	μθ + kx	$e^{-(\mu\theta + kx)}$	Pxi kips	Pav ij kips	Elong ij inch
End A											
1	0.000	0.000	0.000	0.0	0.0	0.000	0.000	1.000	308.0		
2	0.123	0.123	0.031	69.0	69.0	0.014	0.045	0.956	294.6	301.3	6.08
3	0.120	0.243	0.061	50.0	119.0	0.024	0.085	0.919	283.0	288.8	4.22
4	0.163	0.406	0.102	21.5	140.5	0.028	0.130	0.878	270.6	276.8	1.74
5	0.163	0.569	0.142	21.5	162.0	0.032	0.175	0.840	258.6	264.6	1.66
6	0.120	0.689	0.172	50.0	212.0	0.042	0.215	0.807	248.5	253.6	3.71
7	0.120	0.809	0.202	50.0	262.0	0.052	0.255	0.775	238.8	243.6	3.56
8	0.163	0.972	0.243	21.5	283.5	0.057	0.300	0.741	228.2	233.5	1.47
9	0.163	1.135	0.284	21.5	305.0	0.061	0.345	0.708	218.2	223.2	1.40
10	0.120	1.255	0.314	50.0	355.0	0.071	0.385	0.681	209.6	213.9	3.13
11	0.120	1.375	0.344	50.0	405.0	0.081	0.425	0.654	201.4	205.5	3.00
12	0.163	1.538	0.385	21.5	426.5	0.085	0.470	0.625	192.5	197.0	1.24
13	0.163	1.701	0.425	21.5	448.0	0.090	0.515	0.598	184.1	188.3	1.18
14	0.120	1.821	0.455	50.0	498.0	0.100	0.555	0.574	176.8	180.4	2.64
15	0.123	1.944	0.486	69.0	567.0	0.113	0.599	0.549	169.1	173.0	3.49
End B											

Total Tendon Length = 567.0 Feet

Total Force Loss from End A(jack) to End B (dead) = ΔP = $P_1 - P_{15}$ = 138.9 kips

Total elongation (before wedge set) when jacked from End A, ΔA, (ins) = Σ Elong ij = 38.53 inches

** the assumption of a uniform rate of force loss is reasonable for a gradually curving profile.

Average rate of force loss along tendon** = ΔP / L (kip / ft) = 0.245 kip / ft

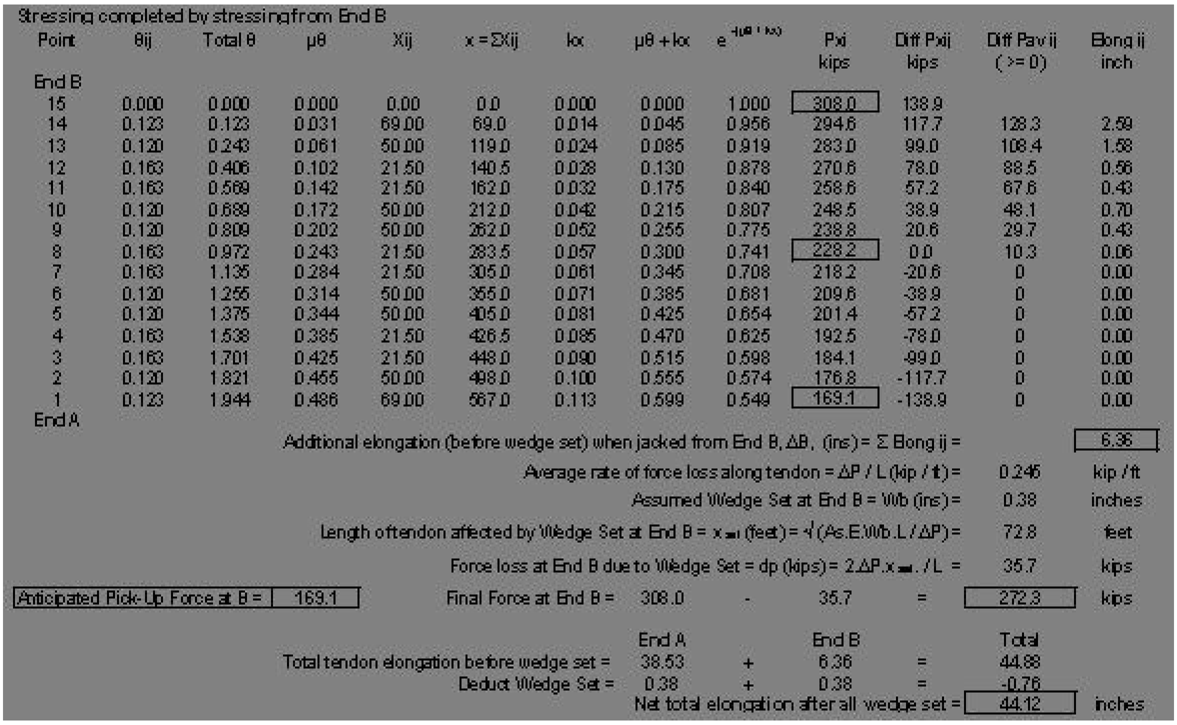
Assumed Wedge Set at End A = Wa (ins) = 0.38 inches

Length of tendon affected by Wedge Set at End A = x [illegible] (feet) = √(As.E.Wa.L / ΔP) = 72.8 feet

Force loss at End A due to Wedge Set = dp (kips) = 2 ΔP.x [illegible] / L = 35.7 kips

Final Force at End A = 308.0 - 35.7 = 272.3 kips

Table 3.1(a) Example 1: Elongation of Profiled Tendon in Four-Span Girder (Fig. 3.2)



Stressing completed by stressing from End B

Point	θij	Total θ	μθ	Xij	x = ΣXij	kx	μθ + kx	$e^{-(\mu\theta + kx)}$	Pxi kips	Diff Pxij kips	Diff Pav ij (>= 0)	Elong ij inch
End B												
15	0.000	0.000	0.000	0.00	0.0	0.000	0.000	1.000	308.0	138.9		
14	0.123	0.123	0.031	69.00	69.0	0.014	0.045	0.956	294.6	117.7	128.3	2.59
13	0.120	0.243	0.061	50.00	119.0	0.024	0.085	0.919	283.0	99.0	108.4	1.58
12	0.163	0.406	0.102	21.50	140.5	0.028	0.130	0.878	270.6	78.0	88.5	0.56
11	0.163	0.569	0.142	21.50	162.0	0.032	0.175	0.840	258.6	57.2	67.6	0.43
10	0.120	0.689	0.172	50.00	212.0	0.042	0.215	0.807	248.5	38.9	48.1	0.70
9	0.120	0.809	0.202	50.00	262.0	0.052	0.255	0.775	238.8	20.6	29.7	0.43
8	0.163	0.972	0.243	21.50	283.5	0.057	0.300	0.741	228.2	0.0	10.3	0.06
7	0.163	1.135	0.284	21.50	305.0	0.061	0.345	0.708	218.2	-20.6	0	0.00
6	0.120	1.255	0.314	50.00	355.0	0.071	0.385	0.681	209.6	-38.9	0	0.00
5	0.120	1.375	0.344	50.00	405.0	0.081	0.425	0.654	201.4	-57.2	0	0.00
4	0.163	1.538	0.385	21.50	426.5	0.085	0.470	0.625	192.5	-78.0	0	0.00
3	0.163	1.701	0.425	21.50	448.0	0.090	0.515	0.598	184.1	-99.0	0	0.00
2	0.120	1.821	0.455	50.00	498.0	0.100	0.555	0.574	176.8	-117.7	0	0.00
1	0.123	1.944	0.486	69.00	567.0	0.113	0.599	0.549	169.1	-138.9	0	0.00
End A												

Additional elongation (before wedge set) when jacked from End B, ΔB, (ins) = Σ Elong ij = 6.36

Average rate of force loss along tendon = ΔP / L (kip / ft) = 0.245 kip / ft

Assumed Wedge Set at End B = Wb (ins) = 0.38 inches

Length of tendon affected by Wedge Set at End B = x [illegible] (feet) = √(As.E.Wb.L / ΔP) = 72.8 feet

Force loss at End B due to Wedge Set = dp (kips) = 2.ΔP.x [illegible] / L = 35.7 kips

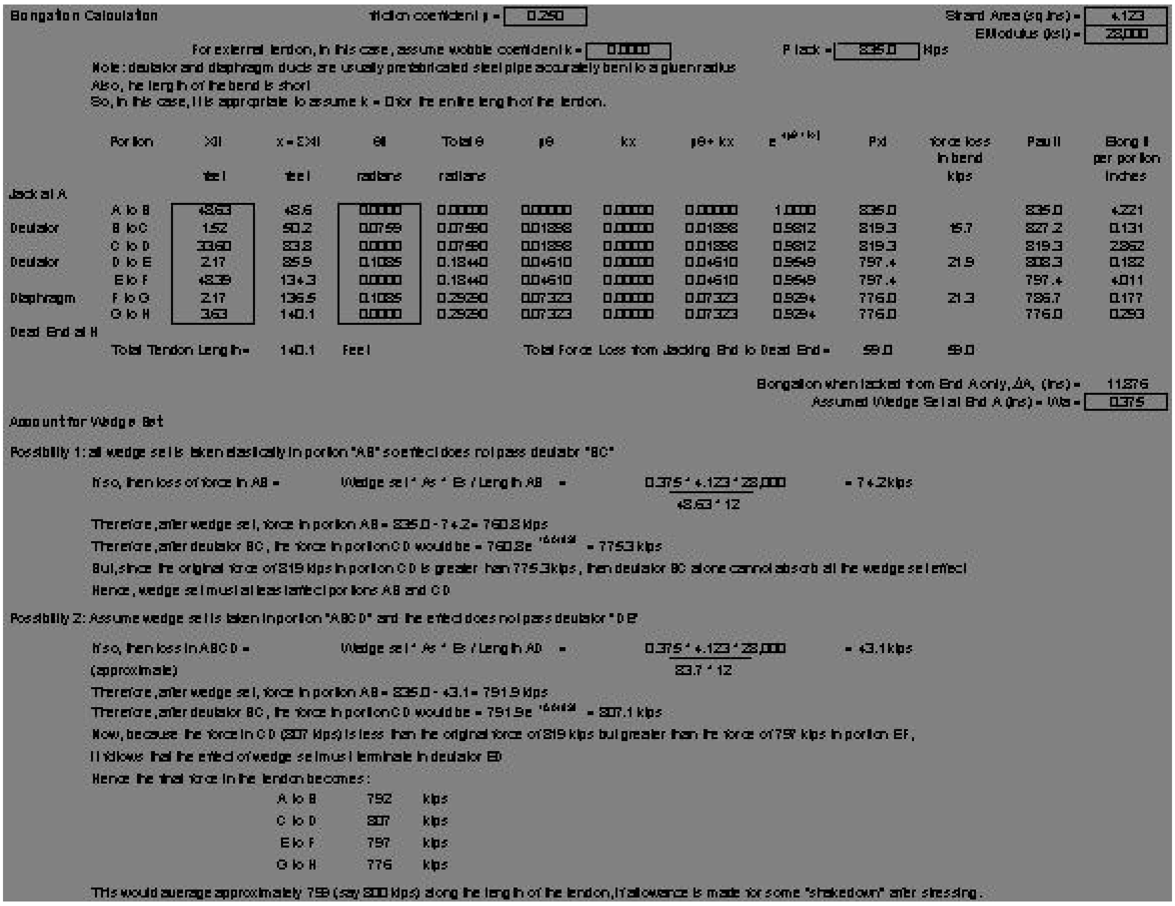
Anticipated Pick-Up Force at B = 169.1

Final Force at End B = 308.0 - 35.7 = 272.3 kips

	End A		End B		Total
Total tendon elongation before wedge set =	38.53	+	6.36	=	44.88
Deduct Wedge Set =	0.38	+	0.38	=	-0.76

Net total elongation after all wedge set = 44.12 inches

Table 3.1(b) Example 1 continued: Elongation of Profiled Tendon in Four-Span Girder (Fig. 3.3)



Elongation Calculation

friction coefficient μ = 0.250

Strand Area (sq ins) = 4.123

E Modulus (ksi) = 28,000

For external tendon, in this case, assume wobble coefficient k = 0.0000

P Jack = 835.0 Kips

Note: deviator and diaphragm ducts are usually prefabricated steel pipe accurately bent to a given radius

Also, the length of the bend is short

So, in this case, it is appropriate to assume k = 0 for the entire length of the tendon.

	Portion	Xi feet	x = ΣXi feet	θi radians	Total θ radians	μθ	kx	μθ + kx	$e^{-(\mu\theta + kx)}$	Px	force loss in bend kips	Pavg	Elong per portion inches
Jack at A													
	A to B	48.63	48.6	0.0000	0.00000	0.00000	0.00000	0.00000	1.0000	835.0		835.0	4.221
Deviator	B to C	1.52	50.2	0.0759	0.07590	0.01898	0.00000	0.01898	0.9812	819.3	15.7	827.2	0.131
	C to D	33.60	83.8	0.0000	0.07590	0.01898	0.00000	0.01898	0.9812	819.3		819.3	2.862
Deviator	D to E	2.17	85.9	0.1085	0.18440	0.04610	0.00000	0.04610	0.9549	797.4	21.9	808.3	0.182
	E to F	48.39	134.3	0.0000	0.18440	0.04610	0.00000	0.04610	0.9549	797.4		797.4	4.011
Diaphragm	F to G	2.17	136.5	0.1085	0.29290	0.07323	0.00000	0.07323	0.9294	776.0	21.3	786.7	0.177
	G to H	3.63	140.1	0.0000	0.29290	0.07323	0.00000	0.07323	0.9294	776.0		776.0	0.293
Dead End at H													
	Total Tendon Length =		140.1	Feet		Total Force Loss from Jacking End to Dead End =				59.0	59.0		

Elongation when jacked from End A only, ΔA, (ins) = 11.876

Assumed Wedge Set at End A (ins) = Wa = 0.375

Account for Wedge Set

Possibility 1: all wedge set is taken elastically in portion "AB" so effect does not pass deviator "BC"

If so, then loss of force in AB = Wedge set * As * Es / Length AB = $\frac{0.375 * 4.123 * 28,000}{48.63 * 12}$ = 74.2 kips

Therefore, after wedge set, force in portion AB = 835.0 - 74.2 = 760.8 kips

Therefore, after deviator BC, the force in portion CD would be = 760.8e [illegible] = 775.3 kips

But, since the original force of 819 kips in portion CD is greater than 775.3 kips, then deviator BC alone cannot absorb all the wedge set effect

Hence, wedge set must at least affect portions AB and CD

Possibility 2: Assume wedge set is taken in portion "ABCD" and the effect does not pass deviator "DE"

If so, then loss in ABCD = Wedge set * As * Es / Length AD = $\frac{0.375 * 4.123 * 28,000}{83.7 * 12}$ = 43.1 kips

(approximate)

Therefore, after wedge set, force in portion AB = 835.0 - 43.1 = 791.9 kips

Therefore, after deviator BC, the force in portion CD would be = 791.9e [illegible] = 807.1 kips

Now, because the force in CD (807 kips) is less than the original force of 819 kips but greater than the force of 797 kips in portion EF,

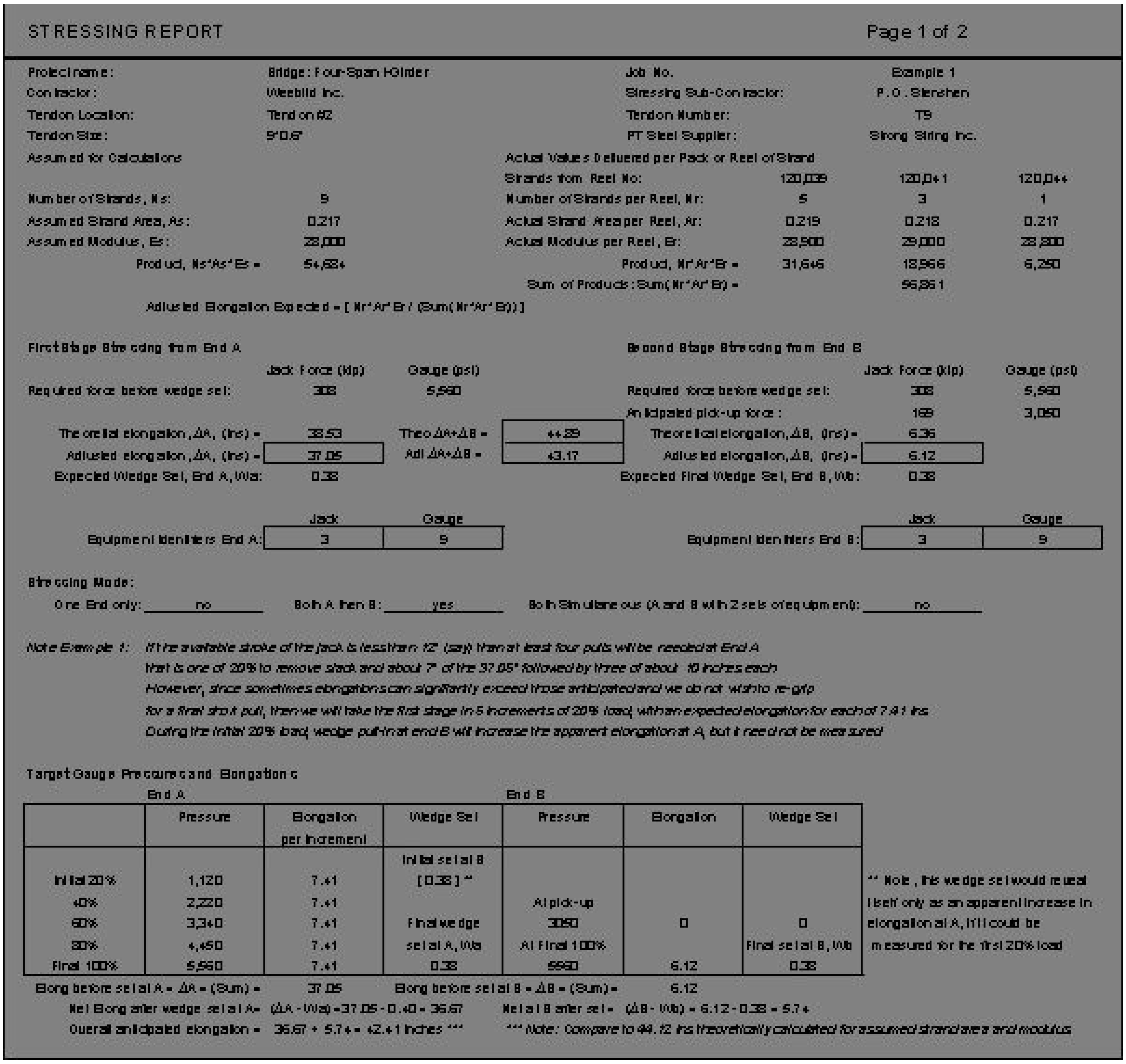
it follows that the effect of wedge set must terminate in deviator ED

Hence the final force in the tendon becomes:

A to B	792	kips
C to D	807	kips
E to F	797	kips
G to H	776	kips

This would average approximately 793 (say 800 kips) along the length of the tendon, if allowance is made for some "shakedown" after stressing.

Table 3.2 Example 2: Elongation of External Deviated Tendon in End-Span (Fig. 3.4)



STRESSING REPORT — Page 1 of 2

Project name:	Bridge: Four-Span I-Girder	Job No.	Example 1
Contractor:	Weebild Inc.	Stressing Sub-Contractor:	P.O. Stershen
Tendon Location:	Tendon #2	Tendon Number:	T9
Tendon Size:	9"0.6"	PT Steel Supplier:	Strong String Inc.

Assumed for Calculations		Actual Values Delivered per Pack or Reel of Strand			
		Strands from Reel No:	120,039	120,041	120,044
Number of Strands, Ns:	9	Number of Strands per Reel, Nr:	5	3	1
Assumed Strand Area, As:	0.217	Actual Strand Area per Reel, Ar:	0.219	0.218	0.217
Assumed Modulus, Es:	28,000	Actual Modulus per Reel, Er:	28,900	29,000	28,800
Product, Ns*As*Es =	54,684	Product, Nr*Ar*Er =	31,646	18,966	6,250
		Sum of Products: Sum(Nr*Ar*Er) =		56,861	

Adjusted Elongation Expected = [Nr*Ar*Er / (Sum(Nr*Ar*Er))]

First Stage Stressing from End A	Jack Force (kip)	Gauge (psi)			Second Stage Stressing from End B	Jack Force (kip)	Gauge (psi)
Required force before wedge set:	308	5,960			Required force before wedge set:	308	5,960
					Anticipated pick-up force:	169	3,050
Theoretical elongation, ΔA, (ins) =	38.53		Theo ΔA+ΔB =	44.89	Theoretical elongation, ΔB, (ins) =	6.36	
Adjusted elongation, ΔA, (ins) =	37.05		Adj ΔA+ΔB =	43.17	Adjusted elongation, ΔB, (ins) =	6.12	
Expected Wedge Set, End A, Wa:	0.38				Expected Final Wedge Set, End B, Wb:	0.38	

	Jack	Gauge		Jack	Gauge
Equipment Identifiers End A:	3	9	Equipment Identifiers End B:	3	9

Stressing Mode:

One End only: no   Both A then B: yes   Both Simultaneous (A and B with 2 sets of equipment): no

Note Example 1: If the available stroke of the jack is less than 12" (say) then at least four pulls will be needed at End A
that is one of 20% to remove slack and about 7" of the 37.05" followed by three of about 10 inches each
However, since sometimes elongations can significantly exceed those anticipated and we do not wish to re-grip
for a final short pull, then we will take the first stage in 5 increments of 20% load, with an expected elongation for each of 7.41 ins
During the initial 20% load, wedge pull-in at end B will increase the apparent elongation at A, but it need not be measured

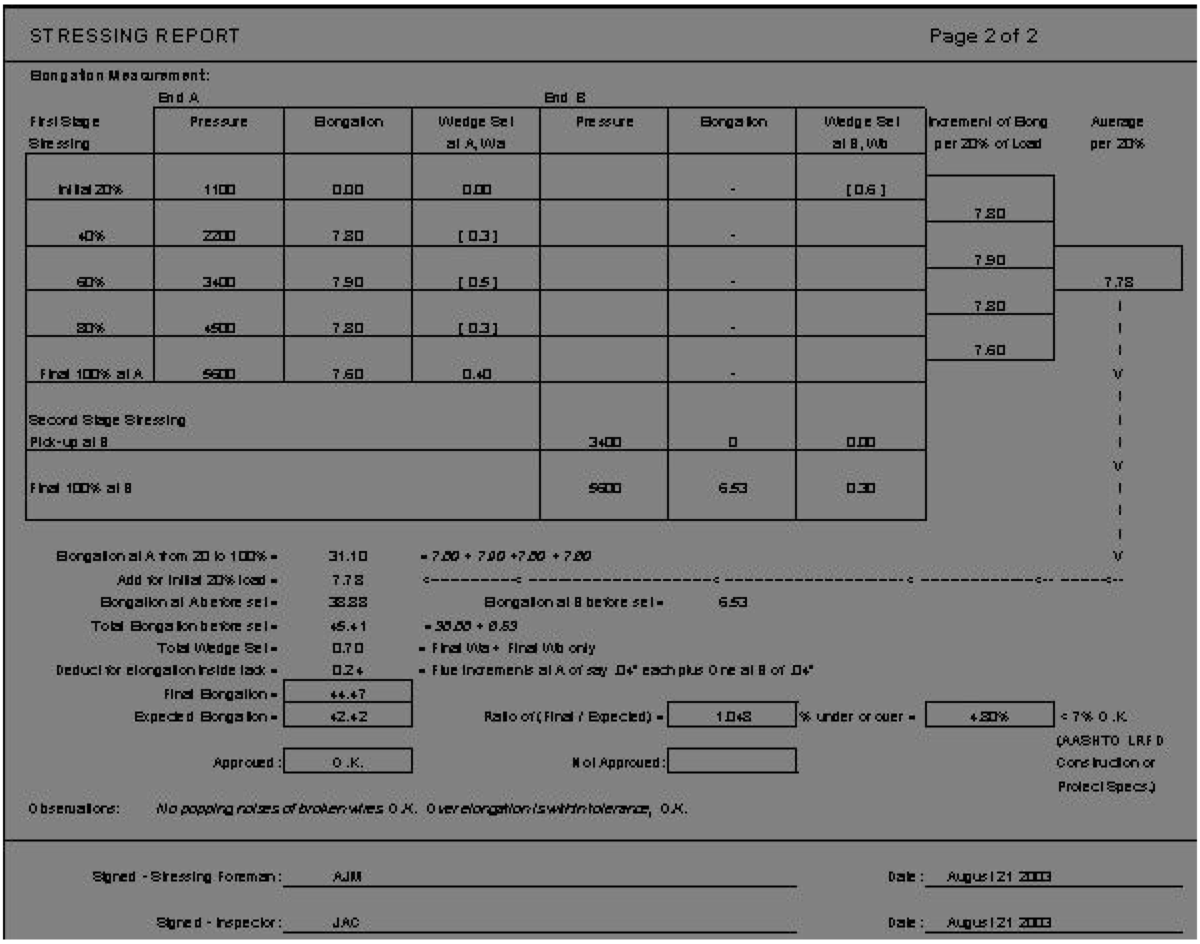
Target Gauge Pressures and Elongations

	End A			End B		
	Pressure	Elongation per Increment	Wedge Set	Pressure	Elongation	Wedge Set
Initial 20%	1,120	7.41	Initial set at B [0.38] **			
40%	2,220	7.41		At pick-up		
60%	3,340	7.41	Final wedge	3050	0	0
80%	4,450	7.41	set at A, Wa	At Final 100%		Final set at B, Wb
Final 100%	5,960	7.41	0.38	5960	6.12	0.38

** Note, this wedge set would reveal itself only as an apparent increase in elongation at A, if it could be measured for the first 20% load

Elong before set at A = ΔA = (Sum) = 37.05   Elong before set at B = ΔB = (Sum) = 6.12
Net Elong after wedge set at A = (ΔA - Wa) = 37.05 - 0.40 = 36.67   Net at B after set = (ΔB - Wb) = 6.12 - 0.38 = 5.74
Overall anticipated elongation = 36.67 + 5.74 = 42.41 inches ***   **** Note: Compare to 44.12 ins theoretically calculated for assumed strand area and modulus*

Table 3.3(a) Stressing Report - Example 1: Profiled Tendon in Four-Span Girder (Fig. 3.2 and 3.3)



STRESSING REPORT — Page 2 of 2

Elongation Measurement:

First Stage Stressing	End A Pressure	Elongation	Wedge Set at A, Wa	End B Pressure	Elongation	Wedge Set at B, Wb	Increment of Elong per 20% of Load	Average per 20%
Initial 20%	1100	0.00	0.00		-	[0.6]		
40%	2200	7.80	[0.3]		-		7.80	
60%	3400	7.90	[0.5]		-		7.90	7.78
80%	4500	7.80	[0.3]		-		7.80	
Final 100% at A	5600	7.60	0.40		-		7.60	
Second Stage Stressing Pick-up at B				3400	0	0.00		
Final 100% at B				5600	6.53	0.30		

Elongation at A from 20 to 100% = 31.10 = *7.80 + 7.90 +7.80 + 7.60*

Add for initial 20% load = 7.78

Elongation at A before set = 38.88 Elongation at B before set = 6.53

Total Elongation before set = 45.41 = *38.88 + 6.53*

Total Wedge Set = 0.70 = Final Wa + Final Wb only

Deduct for elongation inside jack = 0.24 = Five increments at A of say .04" each plus One at B of .04"

Final Elongation = 44.47

Expected Elongation = 42.42 Ratio of (Final / Expected) = 1.048 % under or over = 4.80% < 7% O.K. (AASHTO LRFD Construction or Project Specs.)

Approved : O.K. Not Approved :

Observations: *No popping noises of broken wires O.K. Over elongation is within tolerance, O.K.*

Signed - Stressing Foreman: AJM Date : August 21 2003

Signed - Inspector: JAC Date : August 21 2003

Table 3.3(b) Stressing Report - Example 1 continued: Profiled Tendon in Four-Span Girder (Figs 3.2 and 3.3)

Post-Tensioning Tendon Installation and Grouting Manual

Chapter 4-Grouting of Post-Tensioning Tendons

This Chapter addresses grouting topics generally in the sequence in which operations occur on site. Beginning with a grouting plan, this guidance is provided with regard to equipment, on-site tests of production grout, injection of horizontal and vertical tendons, post-grouting inspection, vacuum grouting to fill any voids and grouting reports to accompany tendon stressing reports. An overview of a few grouting problems and their solutions is provided. Finally, a set of examples for grouting procedures of various types of tendons is offered for information and guidance.

4.1 Grouting Plan

A Grouting Plan should be developed and implemented for construction. In general, project responsibilities regarding the Grouting Plan are:

- Contractor - The Contractor should prepare and submit a "Grouting Plan" according to the requirements of the project specification for post-tensioning and grouting.
- Construction Engineering and Inspection Agency (CEI)-The CEI should record submittals, review and notify the Contractor of the acceptability of his proposed Grouting Plan. The CEI may seek opinion from the Designer, State or Federal Authority regarding the Grouting Plan.

A Grouting Plan typically addresses the following:

- Grouting procedures to be followed at any precast yard and on the job-site as appropriate - this may require separate grouting plans.
- Qualifications and Certification of Grouting Personnel at the precast yard and job-site.
- Proposed grout material and reports of appropriate laboratory qualification tests or evidence to show it meets a pre-qualified or approved product list.
- Storage and protection of all grout material and any additives with procedures to ensure they remain usable or when they must be discarded.
- A source of potable water.
- Means of measuring correct quantities of grout, water and additives.
- Equipment for mixing and testing daily grout production - e.g. type of mixer, pump, storage hoppers, flow-cone, or viscosity meter, samples for strength tests, etc.
- Stand-by equipment - e.g. spare hopper, pump, hoses, flushing equipment, etc.
- If necessary, a means of pressure testing the duct system for leaks and appropriately sealing any leaks so discovered.
- The sequence of injecting and evacuating grout for each type of tendon.
- The location for injecting grout at the low point of each tendon profile.
- The direction of grout injection and sequence of closing vents.

- Provisions for grouting a group of tendons*.
- A means of inspecting to ensure all tendons are completely filled with grout, for example drill and borescope or probe.
- The means and details for sealing grout inlets, vents and drains in any surface - including the top deck (riding) surface if necessary.
- A procedure for secondary grouting using vacuum grouting techniques as necessary in order to fill any voids found by inspection.
- Forms or other means of keeping records of grouting operations (supply copy to CEI for corroboration and witness).
- Temporary PT ducts - procedures to ensure that all internal ducts used for temporary post-tensioning for any purpose are fully grouted at the end of erection, whether temporary PT remains in place or not and whether stressed or not.

* Note: Provisions for grouting of a group of tendons is only necessary in the event of potential cross-over flow between internal tendons at a defect, splice or joint. Group grouting may be needed for efficiency and quality control of operations in some cases. However, normally, internal draped tendons in a cast-in-place superstructure or spliced I-girder are usually grouted one at a time. Prior to group grouting, it is essential to make sure that there is sufficient supply of materials and back-up equipment in case of breakdown. Simultaneous grouting of a group of internal tendons should combine operations for all tendons in that group, recognizing that injection will be done at several injection ports, in sequence or in parallel, with multiple outlets requiring closing in sequence after evacuation of grout of the required consistency.

For information and guidance, examples of procedures to be addressed in a grouting plan or shown on shop drawings for grouting various types of tendons refer to 4.5 below.

4.2 Grout Testing

All materials for grouting should be qualified by appropriate laboratory testing or certification prior to use in the project (Chapter 2).

4.3 Grouting Operations

Grouting should proceed as soon as possible after installation and stressing of the tendons. Depending upon environmental conditions, temporary protection may be necessary and temporary protection of the ends of the strands will be necessary. For example, grout inlets and outlets may be closed drains opened and ends of tendons fitted with temporary caps.

4.3.1 Verification ìof Post-Tensioning Duct System Prior to Grouting

4.3.1.1 Check for Water and Debris

Prior to grouting, tendon ducts, grout inlets and outlets, and anchors, should be examined and debris and water should be removed to avoid blockages or dilution and grout.

4.3.1.2 Proving Ducts with Torpedo

Prior to installing post-tensioning (strand) tendons, it is recommended that ducts be proven for clearance and absence of blockages by passing through a suitably sized torpedo. When proving is done depends upon the particular type of construction - see Chapter 3.

4.3.1.3 Inlets, Outlets and Connections

Connections from grout hose to inlets and outlets should be airtight and free from dirt. Inlets and outlets should be provided with positive shut-offs capable of withstanding the maximum grouting pressure. The required grouting pressure should take into account the pressure head for vertical changes in profile.

Appropriate repairs should be made to any damaged inlets and outlets prior to grouting.

4.3.1.4 Pressure Check of Duct System

Prior to grouting, it is recommended that the post-tensioning ducts be tested using compressed air to verify if any duct connections, joints or fittings require sealing or repair. Compressed air should be clean, dry and free from any oil or contaminants.

A possible test would be to consider the duct system satisfactory if, after pressurizing to an initial pressure (e.g. 0.7MPa (100 psi)) the pressure loss over five minutes is less than 10% (e.g. 0.07MPa (10psi).

Depending upon the type of construction, this test could be run:

1. Before concrete has been placed around ducts in any structure
2. After concrete has been placed but before a girder is shipped from a yard
3. After a girder has been erected and continuity splices made with adjacent girders
4. After precast segments have been erected
5. After post-tensioning strands or bars have been installed

Normally, only one such test would be made as appropriate for the project.

In any case, it would be necessary to temporarily seal the ends of ducts. This could be done with anchor grout caps. Testing to 0.7MPa (100 psi) before concrete placement (1) would be a severe test of a duct system. A lower pressure may be appropriate, according to recommendations of the manufacturer of the ducts and fittings. Testing of a girder before shipping from the yard (2) is suitable only for tendons that begin and end in within the girder and need no splices on site. If a girder has to be spliced to others, then the test should be made on site for the fully continuous duct (3). Longitudinal ducts in precast segments should be tested after erection (4). External tendons can only be tested on site after fabrication of the duct system (4). Temporarily sealing a tendon with long strand tails projecting from anchors is very difficult and is not recommended (5).

Leaks should be sealed in an appropriate manner - such as tightening or re-seating connections and fittings or using a suitable sealant approved by the manufacturer of the PT duct system and acceptable to the Engineer. Leaks at match-cast joints could be sealed by epoxy injection or other acceptable means. In no case should duct tape be used as a seal; however, it may be used to provide temporary support or restraint.

4.3.2 Grouting Equipment

4.3.2.1 Mixer, Storage Hopper, Screen, Pump, Pressure Gauges, Hoses

Mixer

The mixer should be capable of continuous mechanical mixing to produce a homogeneous, stable, grout free of lumps or un-dispersed material that it supplies continuously to the pump.

Mixers are of two main types: vane (or paddle) mixers with a speed of about 1,000 rpm or high-speed shear (colloidal) mixers with a speed of about 1,500 rpm. The high speed mixer distributes cement more uniformly, improves bleed characteristics and minimizes cement lumps.

A high-speed mixer is recommended for pre-bagged grouts.

Storage Hopper and Screen

Most grouting equipment has a mixing (blending) tank which discharges through a screen into a storage hopper or tank mounted over the grout pump (Figure 4.1). The storage hopper should also have a mixing rotor to keep the grout agitated for continuous use and should be kept partially full at all times. The screen should contain openings of 3mm (1/8in) maximum size to screen lumps from the mix. The screen should be inspected periodically. If lumps of cement remain on the screen, then the mix is not suitable.

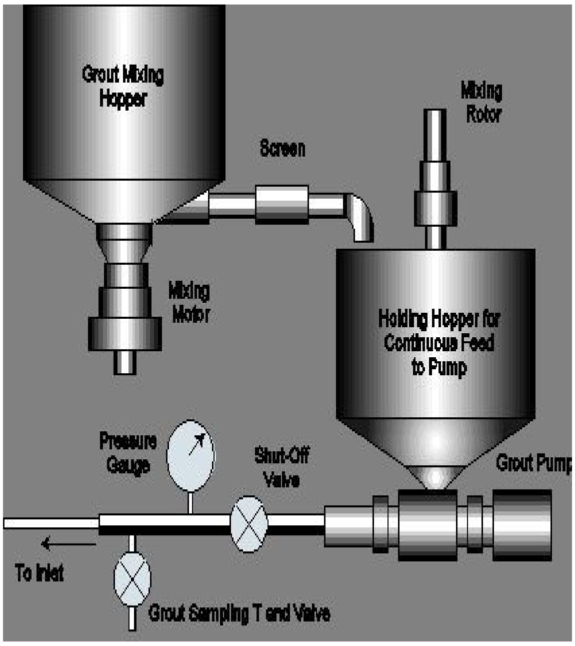


Figure 4.1 - Grout Mixing And Pumping Equipment

For thixotropic grouts, two identical mixing/storage tanks are needed that alternate between blending and storage, so that a new mix can be started while that in storage is pumped. A high-speed (colloidal) mixer is needed for each tank. For thixotropic grouts, the screen between the tank and pump may have openings of 5mm (3/16 in). The grout pump should have precise pressure control and be fed from each holding tank in turn.

Grout Pump

Grout pumps should be of the positive displacement type and able to maintain an outlet pressure of at least 1MPa (145psi) with little variation. The pump, hoses and connections should be able to maintain pressure on completely grouted ducts. A shut-off valve should be installed in the line so that it can be closed off under pressure, as necessary (Figure 4.1).

Pumps with a variable output capability are adaptable to delivery demands of different duct diameters or to group grouting. However, the grouting pressure should be limited to help prevent blow-outs in the equipment, protect operators, prevent excessive segregation or bleed and prevent possible splitting of concrete by over-pressurizing the ducts.

Pumps should have a system for re-circulating the grout when pumping is not in progress and should have seals to prevent oil, air or other foreign substance entering the grout or prevent loss of grout or water. At the pump, grout piping should incorporate a sampling tee with a stop valve. The number of bends and changes in size should be minimized.

Pressure Gauge

A pressure gage with a full scale reading of not more than 2MPa (300 psi) should be attached between the pump outlet and duct inlet. For short lengths (say less than about 10M (30 feet) of grout hose, the gauge may be placed near the pump - for long lengths, at the inlet. For hose lengths over 30M (100 ft), a gage near the pump and one at the inlet may help identify whether sudden pressure build-ups are in the hoses or the ducts.

Hoses

The diameter and pressure rating of hoses should be compatible with the pump and anticipated maximum pressures. All hoses should be firmly connected to pump outlets, pipes and inlets. It is recommended that grout hoses be at least 20mm (¾ in) inside diameter for lengths up to about 30M (100 ft) and that a reduction in size at connectors be avoided. Also, narrow openings should be avoided. Both can lead to pressure build-up and possible risk of blockage.

4.3.2.2 On-Site Test Equipment for Production Grouting

For sampling and testing daily production of fluid grout the following equipment should be available:

- Clean containers for sampling.
- Flow-cone, 1 liter container and stop-watch for fluidity (ASTM C939, Figure 2.1).
- American Petroleum Institute (API) Mud-Balance for density tests.
- 50mm (2 inch) moulds for making strength test cubes.
- Graduated cylinders and strand sample for Wick Induced Bleed Test (ASTM C940).
- For thixotropic grout - Schupack Pressure Grout Test kit (Figure 2.3)

Specification requirements for field testing may vary by project and not all of the listed equipment may be necessary.

4.3.2.3 Vacuum Grouting Equipment:

When project contract documents require vacuum grouting, equipment should be provided at the job-site concurrently with all pressure grouting operations (Figure 4.2). Vacuum grouting equipment should be of the volumetric measuring type with the ability to measure the volume of a void and supply a measured volume of grout to fill that void.

Provisions for vacuum grouting are usually not necessary for projects containing only transverse (deck slab) tendons with a length of less than 30M (100 ft).

Digital Volumer

Void Volume Measurement

Grout Pump

Vacuum Grout Injection

Figure 4.2 -Vacuum Grouting Equipment

4.3.2.4 Stand-by Grouting Equipment

A standby grout mixer and pump should be available during grouting operations.

An air-compressor is needed for a supply of oil-free compressed air for checking ducts for integrity and leaks or help blow out any water. Lengths of air hose should be sufficient to insert and reach along ducts to blow debris or water out as necessary.

Adequate flushing equipment and potable water supply should be available in the event it is necessary to completely remove grout from a duct. However, although flushing has been required in the past, it is no longer recommended. As remedial action, removal of grout should be done only with the concurrence of the Engineer when necessary. Vacuum grouting is a preferred method for grouting partially filled ducts in most situations.

4.3.2.5 Clean Grouting Equipment

All grouting equipment should be thoroughly cleaned after grouting.

4.3.3 Batching and Mixing

The proportions in the mix should be based upon the mix approved prior to grouting is begun whether for a mix to be blended on site or for a pre-qualified, pre-bagged grout (Chapter 4). Dry powder and pre-bagged grout materials should be batched by weight to an accuracy of +2%. Water and liquid admixtures may be batched by weight or volume to an accuracy of +1%. Any water content in any liquid admixtures should be counted toward the quantity of water.

The materials should be mixed to produce a homogeneous grout without excessive temperature rise or loss of fluid properties (flow cone). The mix should be continuously agitated until it is pumped. Water must not be added to increase fluidity if it has decreased by delayed use of the grout. Typically, the mix time for grout should be in accordance with the qualification trials and generally not more than 4 minutes for a vane mixer or 2 minutes for a high-speed shear mixer.

Unless otherwise specified by the manufacturer, the constituents may be added as follows:

- For a vane mixer: all the water, about 2/3 cementitious material, the admixture, the remaining water.
- For a high speed shear (colloidal) mixer: water, admixture, cementitious material

Condensed, dry compacted silica fume should not be added to a mix as it agglomerates and does not blend well, leading to a poor mix.

4.3.4 On-Site Tests of Production Grout

In order to ensure the correct consistency and density of daily production grout, fluidity and density should be within acceptable limits according to the following requirements. Additional water must never be added to a mix to meet fluidity test requirements and surplus, discharged and tested grout should be properly discarded.

It is recommended that daily production grout be monitored before and after injection according to the tests in the following Sections.

4.3.4.1 Production Bleed Test - Prior to Injection

For normal (non-thixotropic grouts) it is recommended that at the beginning of each day's production grouting, either a wick induced bleed test (Figure 2.2) be performed on the mix for that day or a Schupack Pressure Bleed Test (Figure 2.3).

Because the wick induced bleed test takes at least three hours, discretion must be exercised to avoid unnecessary delay when starting new (daily) grouting operations. Consequently, it is suggested that this test be performed regularly on currently stored materials intended for use in the near term so that acceptable results can be routinely maintained to facilitate continued production grouting.

As an alternative, the Schupack Pressure Bleed Test should require less time and should be suitable for most manufactured (pre-bagged) grouts. Reference should be made to the manufacturer. Information on the test may be found in Appendix C of the PTI "Specification for Grouting of Post-Tensioned Structures", (latest edition).

4.3.4.2 Normal, Non-Thixotropic, Grout - Prior to Injection at Inlet

The consistency of non-thixotropic grouts should be tested according to ASTM C939 "Standard Test Method for Flow of Grout". The efflux time should be between 11 and 30 seconds immediately after mixing. After allowing the grout to stand for 30 minutes without further agitation, the efflux time should be less than 30 seconds.

4.3.4.3 Thixotropic Grout - Prior to Injection at Inlet

For thixotropic grouts, the modified ASTM C939 test should be used where the flow cone is filled to the top, i.e. above the standard level, and the time to fill a one-liter container is measured. The efflux time should be between 5 and 30 seconds immediately after mixing. After allowing the grout to stand for 30 minutes without agitation and then remixing for 30 seconds, the efflux time should be less than 30 seconds.

[Note: The modified flow-cone may not be suitable for some types of thixotropic grout. It is understood to give different results for different grout manufacturers. An alternative test that measures the spread diameter of a collapsed cylinder of grout is under consideration by industry. It was developed for off-shore projects in Norway and Sweden.]

The density of a thixotropic grout may be sampled and checked at the inlet using the "mud-balance" test of the American Petroleum Institute (API) (ASTM C185).

4.3.4.4 Normal, Non-Thixotropic, Grout - Discharge at Final Outlet

Immediately after a uniform flow of uncontaminated grout is obtained at the last outlet, a fluidity test should be performed on the grout discharged from the outlet using the standard ASTM C 939 flow cone test (Figure 2.1). The efflux time should not be less than that measured at the pump / inlet. If the efflux time is too short, then more grout should be discharged and test again. This should be repeated until the grout has an acceptable uniform consistency: i.e. a minimum acceptable efflux time of 11 seconds providing that the maximum efflux time is less than 30 seconds.

Alternatively, the fluidity and density of the discharged grout may be checked using the Wet Density Method for field samples (ASTM C 138). The measured density should fall within acceptable values.

4.3.4.5 Thixotropic Grout - Discharge at Final Outlet

Immediately after a uniform flow of uncontaminated grout is obtained at the last outlet, a fluidity test should be performed on the grout discharged from the outlet using the modified ASTM C 939 flow cone test (Figure 2.1). The maximum efflux time should be less than 30 seconds. Alternatively, the density of the discharge grout may be checked using the API mud-balance. [Note: This may be a more suitable method for certain commercial, thixotropic and highly fluid grouts with very short efflux times of a few seconds. The density at the outlet should not be less than that measured at the pump / inlet.]

4.3.5 Injection of Grout

Prior to grouting, all grout outlets should be opened and checked to ensure they are free and clear of any debris and water. Grouting should proceed according to an approved Grouting Plan (4.1).

4.3.5.1 Pumping

Grout pumping methods should ensure complete filling of the ducts and encasement of post-tensioning steel. Grout should be pumped in a continuous operation and be ejected from the first, and subsequent outlets, until all visible slugs of water or entrapped air have been removed prior to closing each outlet in turn. At each outlet and final grout cap, pumping should continue until the consistency of the discharged grout is equivalent to that being injected at the inlet. At least 7.5 liters (2 gallons) of good, consistent, quality grout should be discharged through the final anchor and cap before closing them.

4.3.5.2 Limiting Grout Injection Pressures

For normal operations grout should be injected at a pressure of less than 0.52 MPa (75psi) at the inlet. Pumping pressures should not exceed 1MPa (145 psi).

Although higher pressures than this might be sustained by internal ducts of HDPE or steel or external ducts of steel pipe, higher pressures are not recommended for grouting. Sometimes an initial temporary higher pressure may be needed to mobilize a thixotropic grout, but, once flowing, pumping pressures should be the same as for normal grouts.

4.3.5.3 Grout Flow Rate

Unless otherwise approved by the Engineer, grout should be injected at a rate of 16 feet [5M] to 50 feet [15M] of duct per minute under normal pumping pressures.

4.3.6 Grout Injection of Superstructure Tendons

4.3.6.1 Locations of Inlets and Outlets.

For information and guidance, refer to examples of recommended locations of grout inlets and outlets in 4.5 below.

4.3.6.2 Sequence of Using and Closing Outlets

For generally horizontal or draped tendons, grouting should proceed from an inlet at the lowest point of the tendon profile. This may be at an initial anchor or at an intermediate low point in the tendon profile.

Grout should be injected steadily and consistently at the designated inlet. When grout flow through the first intermediate outlet is of a consistency of that being injected and is free of all slugs of air or water, the first outlet may be closed. Injection should continue until the same flow is obtained from the next outlet in turn, whereupon it should be closed. Grouting injection should continue until all intermediate outlets have been closed and grout flows from the last anchor outlet. Grouting should continue until at least 2 gallons of grout have been discharged through the last anchor and its grout cap in order to ensure that the anchor and cap are fully filled.

If during injection, the actual grouting pressure exceeds the maximum allowed at the inlet, then the inlet should be closed and the grout pumped in at the next available vent, providing that grout has already flowed from that vent - so that one-way grout flow is maintained.

For further information and guidance, see 4.5 below.

4.3.6.3 Grout Pressure Test for Leaks

Checking a grouted tendon should primarily be in accordance with AASHTO LRFD Construction Specifications. Reference may also be made to the PTI Grouting Specification.

The following alternative method has been adopted by FDOT and is included for information only:

"After all outlets have been bled and closed, the pressure should be raised to approximately 0.52MPa (75psi) and held for two minutes while the tendon is examined for any evidence of leaks and avoid the unintended loss of grout. A drop in pressure during the two minute period would indicate leaks. In order to check pressure loss, a pressure gage should be placed in the line between the exit valve at the pump, which is closed off under pressure, and the tendon inlet, which is left open. Alternatively, a pressure gage could be installed at any convenient outlet. Leaks should be sealed using methods approved by the Engineer and the pressure test repeated."

4.3.6.4 Release Entrapped Air and Lock-Off

Checking a grouted tendon should primarily be in accordance with AASHTO LRFD Construction Specifications. Reference may also be made to the PTI Grouting Specification.

The following alternative method has been adopted by FDOT and is included for information only:

"When there are no leaks or when they have been properly sealed, the 0.52MPa (75 psi) pressure should be released to 0.03MPa (5psi) for ten minutes to allow any entrapped air to flow to high points. After ten minutes, the grouting pressure should be increased as necessary in order to release any entrapped air or water and discharge grout at each of the tendon high point outlets in turn. The system should then be locked off at a pressure of 0.21MPa (30psi)."

4.3.6.5 Incomplete Grouting

When complete grouting by the above methods cannot be achieved, then the grouting operation should be terminated. After 24 hours (i.e. after the grout has set), the tendon should be inspected, if necessary, by drilling and using an endoscope or probe (4.3.8). Voids should be measured and filled using volumetric measuring vacuum grouting or other methods approved by the Engineer. The disposition of a blocked tendon will be a project specific determination.

4.3.7 Grout Injection of Vertical Tendons

This Section addresses the grouting of conventional post-tensioning systems in vertical applications. Grouting of Cable-Stays is not addressed in this document.

4.3.7.1 Grout Material

Grout for relatively short vertical tendons such as vertical PT bars in webs or diaphragms of a superstructure may be the same as that used in longitudinal tendons. However, for applications in tall piers or towers, a grout with very low bleed characteristics is essential and it may be necessary to inject the grout in intermediate lifts.

4.3.7.2 Standpipes

For vertical tendons, a standpipe should be provided at each upper end to store bleed water and grout and to maintain the grout level above the level of the prestressing anchorage and grout cap. The pipe should be designed and installed so to ensure that bleed will at no time cause the level of the grout to drop below a point established on the standpipe at least 0.3M (1 foot) above the highest point of the anchorage and cap and so that all bleed water rises into the standpipe and does not accumulate in the anchorage and cap. Clear plastic pipe is suitable for a standpipe.

4.3.7.3 Grout Injection

Grout should be injected at the lowest point and discharged through the standpipe. The fluidity and density of the grout before and after injection should be checked. The standpipe should be filled so that the level does not drop below the anchorage and cap. If, after ceasing active pumping, the level drops below the level established on the standpipe, grout should be immediately added to the standpipe.

For vertical tendons in excess of 30M (100 ft) high, or if the grouting pressure exceeds 1MPa (145 psi), then grout should be injected at higher outlets from which grout has already flowed, so that one-way flow of grout is maintained. Grout should be allowed to flow from an outlet until all air and water has been purged prior to using that outlet for injection

4.3.7.4 Incomplete Grouting

When complete grouting by the above methods cannot be achieved, then the grouting operation should be terminated. After 24 hours (i.e. after the grout has set), the standpipe should be removed and the anchorage and cap examined to make sure that they are completely full; if necessary by drilling and using an endoscope or probe (4.3.8). Voids should be measured and filled using volumetric measuring vacuum grouting.

It is preferred that partially complete grout not be flushed out with water - this is not only difficult but it is impossible to remove all excess water. This will lead to excessive bleed upon re-grouting - especially if flushing is only partially successful. Grout should only be flushed out when given the approval of the Engineer. In extreme cases, removal of grout may require high pressure hydro-demolition. If removal in this fashion is required, all the grout and tendon should be removed.

4.3.8 Post-Grouting Inspection

It is recommended that all inspections be performed in the presence of the Inspector (CEI).

4.3.8.1 Opening Inlets and Outlets for Inspection

Valves, caps and pipes at inlets and outlets should not be removed or opened until the grout has set and cured for a minimum of 24 hours after grouting. However, within 72 hours of grouting, all inlets and outlets should be opened to facilitate inspection. Inspection of the grout should be performed within one hour of opening.

All inlets and outlets should be inspected to ensure complete filling with grout. All inlets and outlets should be capped and sealed (below) within four (4) hours of the completion of inspection, completion of vacuum grouting or removal of non-inspected inlets and outlets.

Vacuum-grouting, when necessary, should be completed within 72 hours of inspection.

4.3.8.2 Drill Grout to Verify Absence of Voids

At anchorages, sometimes, depending upon geometry, it is possible that an inlet or outlet may appear to be filled, but a void may exist inside the anchor trumpet or duct. Consequently, the grout inlet or outlet at the anchorage should be drilled just sufficient to penetrate the inner surface of the trumpet or duct. Drilling equipment should have an automatic shut-off when steel is encountered so that the tendon is not damaged. Grout caps over anchorages should not be drilled unless voids are suspected by sounding.

Grout outlets (pipes) or inlets in the duct between anchorages should be installed in such a way that they can be drilled just sufficient to penetrate the inner surface of the duct and then be inspected in the same way as at an anchorage.

When a void is found, it should be examined to determine its extent. All voids should be completely filled using the volumetric measuring vacuum grouting process.

4.3.8.3 Frequency of Inspection

For longitudinal superstructure tendons, the following frequency of inspection is suggested:

- All inlets and outlets at anchors and tendon high points should be inspected by drilling and probing with an endoscope to detect defects (voids).
- For bridges with more than 20 tendons but where no tendon is longer than 50M (150ft) all inlets and outlets at anchors and tendon high points should be inspected by drilling and probing with an endoscope or probe until no defects (voids) are found in twenty (20) consecutive tendons. Thereafter,

inspection may be reduced by 50% i.e. to every other tendon. However, if a defect is found, then the last five tendons grouted should be inspected and the next 20 consecutive tendons should be inspected before once again reducing the frequency of inspection to 50% if no voids are found. This cycle should continue for throughout all tendon grouting operations.

For relatively short vertical tendons in superstructure webs or diaphragms, the top (anchor) outlet of each tendon should be inspected. All inlets and outlets should be inspected for vertical tendons in substructures.

4.3.8.4 Filling Drilled Inspection Holes

Drilled inspection holes that do not encounter voids should be filled with an approved cementitious grout or epoxy using an injection tube extending to the bottom of the drilled hole.

4.3.8.5 Incomplete Grouting

In general, when any tendon grouting operations have been prematurely terminated before the ducts could be completely filled with grout, ducts should be drilled into and explored for voided areas using an endoscope in order to determine the extent and volume of voids. Grout inlets and outlets should be installed and the voids filled using volumetric measuring vacuum grouting equipment.

4.3.9 Filling Voids by Vacuum Grouting

Vacuum grouting is a method of withdrawing air from voids to create as complete a vacuum as possible and then using this vacuum to draw grout in to fill the voids. The efficiency of the method depends significantly upon the degree to which all leaks can be effectively sealed. Since it is impossible to create a complete vacuum, most operations are done under a partial vacuum. Also, grout is normally injected under pressure - so the method may be referred to as "vacuum assisted pressure grouting".

Leaks at anchorages, grout inlets or outlets can usually be sealed by tightening grout caps. However, it is difficult to seal a leak somewhere along the length of a tendon at a breach in the duct wall, at a poorly made duct splice or if there is cross-communication between ducts through incompletely sealed epoxy joints or defects in concrete. A positive air pressure test should reveal the presence of such leaks. As far as possible, such leaks should be sealed with epoxy or epoxy injection.

Vacuum grouting equipment should include a device for measuring the volume of the voids so that the amount of grout injected can be checked against that anticipated to give some assurance that the voids have been filled. Most devices function on the basis of measuring pressure changes when voids are connected to an evacuated pressurized vessel of known volume or vice-versa.

If a void has a constriction, say somewhere along a tendon, it may not be possible to inject grout beyond it. Consequently, the volume of vacuum injected grout will be less than the measured volume. An attempt should then be made to complete the vacuum grouting from the other end, if possible. If the location of a constriction is known, or if a void exists somewhere in the center of the tendon and dos not connect with the ends, it may be possible to carefully drill into the duct and install intermediate grout inlets and outlets for vacuum grouting.

4.3.9.1 Time for Completion of Vacuum Grouting

When vacuum grouting is necessary, it is should be completed within 72 hours of the inspection of the inlets and outlets by drilling and probing. Caps and seals should be completed within four (4) hours of the completion of vacuum grouting.

4.3.9.2 Grout Material

Unless otherwise approved by the Engineer, grout for vacuum grouting should be the same as that used to grout the tendons.

4.3.9.3 Equipment

Mixer

Because vacuum grouting usually involves relatively small quantities of grout, the grout mixer and storage hopper need not necessarily be the same as that for main grouting operations. However, mixer must be capable of thoroughly mixing the constituents to meet fluidity and other requirements for normal or thixotropic grouts.

Volumeter

A device referred to as a "volumeter" is needed to measure the volume of the grout voids. This device may use either a vacuum or air pressure method. It may be an analog or digital device.

Grout Hopper and Pump

A grout pump should be a positive displacement (piston and cylinder) device with a suitable sized hopper and attachments for hoses.

Hoses and Valves

Hoses and valves are needed to connect an air compressor or vacuum pump with the volumeter, grout pump and duct inlet. Valves should be installed as necessary to facilitate evacuation of the air from the voids, measurement of the volume of void and switching over to inject grout under pressure.

4.3.9.4 Vacuum Grouting Operation

Vacuum grouting generally involves the following activities:

- Pressurize void and check for leaks.
- Seal leaks (tighten all caps and seal leaks with epoxy or epoxy injection).
- Measure the volume of the void to determine the necessary quantity of grout.
- Mix sufficient grout for use and for testing, record quantity of mixed grout.
- Test the grout using the flow-cone or modified flow-cone method.
- Evacuate air from the voids.
- Switch valve and inject grout into voids under pressure.
- Record quantity of grout remaining and calculate the amount injected.
- Seal grout injection inlets.
- Clean equipment, area of operations on structure and properly discard unused grout.
- Record and report vacuum grouting operations.

4.3.10 Sealing of Grout Inlets and Outlets

It is recommended that threaded plastic caps be used to seal all grout inlet and outlet pipes and that threaded plugs be installed in anchorages and grout caps once the grout pipe and shut-off valve have been removed (Figure 2.9).

Where an inlet or outlet is permanently recessed within the concrete, provision should be made to accommodate the threaded plastic cap at clear depth of at least 25mm (1in) by means of a formed recess. The recess should be cleaned and completely filled with an approved epoxy material. The surface of the recess should be prepared to receive the epoxy material in accordance with the recommendations of the manufacturer of the epoxy (Appendix D).

4.3.11 Protection of Post-Tensioning Anchorages

After grouting, all post-tensioning anchorages should be properly prepared and protected as necessary. For further information, refer to Appendix D.

4.3.12 Grouting Report

A report on tendon grouting, inspection, vacuum grouting and sealing should be provided from the Contractor to the Engineer within 72 hours of the completion of sealing. The tendon grouting report should include, but need not necessarily be limited to:

- Project identification
- Bridge identification
- Identification of the tendon
- Date tendon was stressed
- Date grouted
- Number of days from stressing to grouting
- Type of grout (cement type, pre-bagged, manufacturer)
- Tendons grouted in same grouting operation
- Injection end
- Applied grouting pressure
- Ratio of actual to theoretical quantity of grout
- Summary of any problems with grouting and corrective action taken
- Date of filling voids by vacuum grouting
- Estimated volume of voids measured during vacuum grouting process
- Quantity of grout injected by vacuum grouting
- Summary of any problems with vacuum grouting and corrective action taken
- Confirmation and date of sealing of inlets and outlets
- Type of epoxy used to fill recesses containing sealed inlets and outlets.

The "Grouting Report" should be coordinated with the "Stressing Report".

4.4 Grouting Problems and Solutions

4.4.1 Interruption of Grout Flow

If there is a breakdown, then use the available standby equipment. Standby equipment should be periodically checked to make sure it is in working order. Standby equipment may be a second set of production grouting equipment in operation nearby. In any event, standby equipment should be mobilized as soon as possible.

Standby equipment should be brought into operation within 15 to 30 minutes or else grout may begin to solidify and it will be too difficult to mobilize the grout, especially on long tendons.

If standby equipment cannot be brought into operation, then the grouting should be terminated.

The grout should be inspected (4.3.8) and completed using vacuum grouting (4.3.9) or other approved methods and procedures proposed by the Contractor and approved by the Inspector (CEI).

4.4.2 Too High Grouting Pressure

If it requires excessive pressure to inject grout, there may be a blockage. Excessive pressure would be any pressure about 50% more than the limiting pressure in 4.3.5.2. In no circumstances should attempts be made to force grout through. Excessive pressure can lead to failure of ducts or cracking of concrete, depending upon circumstances and details.

If grout cannot be injected at an intermediate outlet from which it has already flowed, grouting should cease. The grout should be inspected (4.3.8) and completed using vacuum grouting (4.3.9) or other approved methods and procedures proposed by the Contractor and approved by the Inspector (CEI) (See also 4.3.6.2 and 4.3.7.3).

4.4.3 Flushing of Incomplete Grout

It is preferred that flushing of incomplete grout not be used (4.3.6.5 and 4.3.7.4) unless it is unavoidable under some very special circumstance - in which case it should only be done with the approval of the Inspector (CEI).

4.4.4 Unanticipated Cross-Grouting

The risk of cross-grouting should be detected by the duct pressure test (4.3.1.3) and action taken to accommodate grouting of the tendons as a group (see requirements for the Grouting Plan (4.1).

If, however, cross grouting is discovered only during production grouting, then if the other affected tendons have already been satisfactorily stressed, grouting should continue until all tendons affected by cross-grouting have been fully grouted. If cross grouting is into empty ducts or ducts containing tendons that have not yet been stressed, then grouting should stop and the affected ducts or tendons should be flushed. After the incomplete grout has set in the leaking tendon, leaks should be sealed using appropriate and approved techniques (e.g. epoxy injection). Grouting should be inspected (4.3.8) and completed using vacuum grouting (4.3.9).

4.4.5 Production Grout Fluidity Unacceptable

Prior to grouting, if the flow-cone time exceeds the allowable limits, perform another test. If the flow time still exceeds allowable limits, check the source, date, storage and mixing of grout materials.

Do not add water or any high-range water reducer to improve fluidity. If necessary, abandon the batch and begin again with new material.

4.5 Examples of Grouting Procedures

The following are offered for guidance. This is not an exhaustive set of examples for all conceivable circumstances and should be considered only for information and guidance.

4.5.1 Example 1: Two-Span Spliced I-Girder(Figure 4.3)

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- Orient end anchors (A and G) so that the vents are at the top.
- Determine location at lowest point of profile for injection vent (in this example, point B). Because, in this case, the profile change in the depth of the spliced I-girder is significant (i.e. greater than 0.5M (20in)) grout should be injected from the low point. If two or more low points are at the same elevation, then select one.
- Provide a vent at crest (D) and at 1 to 2M (3 to 6 feet) beyond crest (at C and E) in both directions (to avoid potential confusion between work at precast plant and site).
- Provide drainage vents at other low points (B and F).
- Provide grout outlet at end anchor (G).
- Show direction of grouting.
- Sequence of closing vents: A, C, F, E, D, G, B.

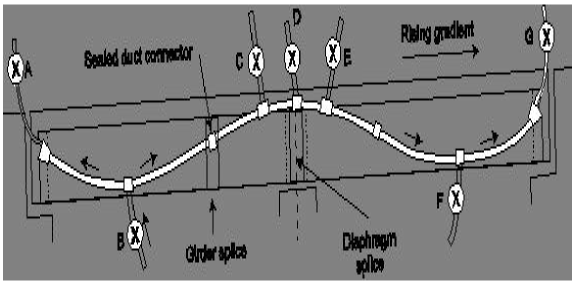


Figure 4.3 - Grouting details for a 2-span spliced girder duct system

4.5.2 Example 2: Four-Span Spliced I-Girder (Figure 4.4)

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- Orient end anchors (A and O) so that the vents are at the top.
- Determine which location is at lowest point of profile for injection vent (in this example point B). Because, in this case, the profile change in the depth of the spliced I-girder is significant (i.e. greater than 0.5M (20in)grout should be injected from the low point. If two or more low points are at the same elevation, then select one.
- Provide vent at all crests (D, H, L) and at 1 to 2M (3 to 6 ft) beyond crests (at C, E, G, I, K, and M). Although it is only necessary, in theory, to install outlets at the high points and on the downstream side of each crest, in order to avoid confusion and risk of a mistake (such as turning girder end for end) during erection, it may be prudent to install vents on both sides of a crest.

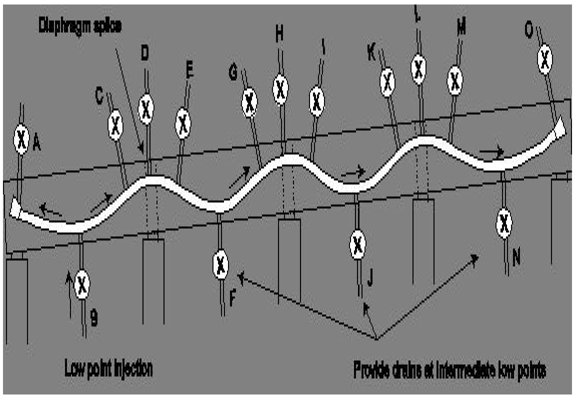


Figure 4.4 - Grouting details for a 4-span spliced girder duct system

- Provide drainage vents at all other low points (B, F, J, and N)
- Provide grout outlet vent at end anchor (O).
- Show direction of grouting.
- Sequence of closing vents: A, C, F, E, D, G, J, I, H, K, N, M, L, O, B.

4.5.3 Example 3: Cantilever and Drop-In Spliced 3-Span I-Girder (Figure 4.5)

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- Because, in this case, the profile change in the depth of the spliced I-girder is significant (i.e. greater than 0.5M (20in)) grout should be injected from low point.
- Determine which location is lowest for injection vent (in this example, point B).
- Orient end anchors (A and L) so that vents are at top.

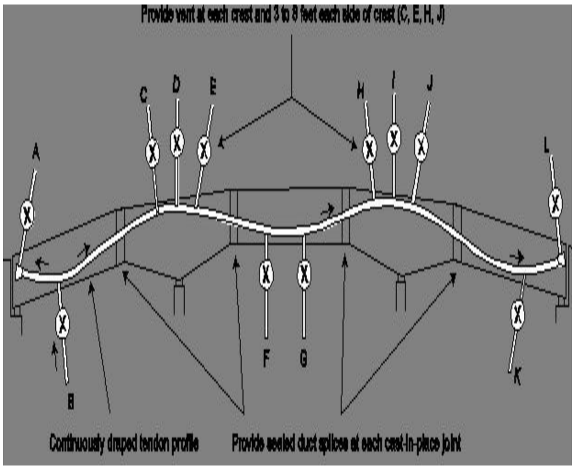


Figure 4.5 -Grouting details for a 3-span, drop-in and spliced girder duct system

- Provide vent at crests (D and I) and at 1 to 2M (3 to 6 ft) from crests (at C, E, H and J). Although it is only necessary, in theory, to install outlet vents at the high points and on the downstream side of each crest, in order to avoid risk of mistake (such as turning girder on end) during erection, it may be prudent to install vents on both sides of a crest.
- Provide drainage vents at all other low points (B, F, G and K).
- Provide grout outlet vent at end anchor (L).
- Show direction of grouting.
- Sequence of closing vents: A, C, F, G, E, D, H, K, J, I, L, B.

4.5.4 Example 4: Cast-in-Place on Falsework(Figure 4.6):

This example applies to any type of structure cast-in-place on falsework such as boxes, solid slabs and voided slabs.

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- If the change in depth of the tendon profile is more than 0.5M (20 in), grout should be injected from a low point. If two or more low points are at same elevation, select one.
- Provide outlet vents at end anchors (A and I).
- Orient end anchors (A and I) so that grout vents are at top.
- Provide outlet vents at high point crest of profile, allowing for grade - (i.e. at C and F).

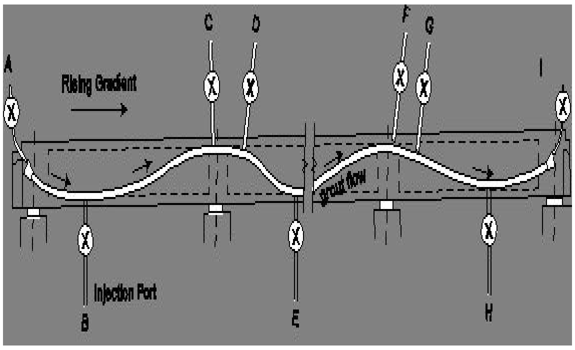


Figure 4.6 - Grouting details for cellular box, voided or solid slab duct system

- Provide outlet vents at point approximately 1 to 2M (3 to 6 ft) beyond crests in direction of grout flow - (e.g. at D and G).

- Determine which location is at lowest point of profile for injection vent (e.g. point B).
- Provide drainage vents at other low points (E and H).
- Show direction of grouting.
- Sequence of closing vents: A, E, D, C, H, G, F, I, B.

4.5.5 Example 5: Cantilever or Top Continuity Post-Tensioning (Figure 4.7):

For a typical cantilever tendon, where the cantilever is on a rising longitudinal gradient, the following procedure would. It would also apply to a similar top slab continuity tendon.

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- Orient end anchors (A and D) so that grout injection and evacuation vents are at top.
- Provide grout inlet at lowest, end anchor, (A).

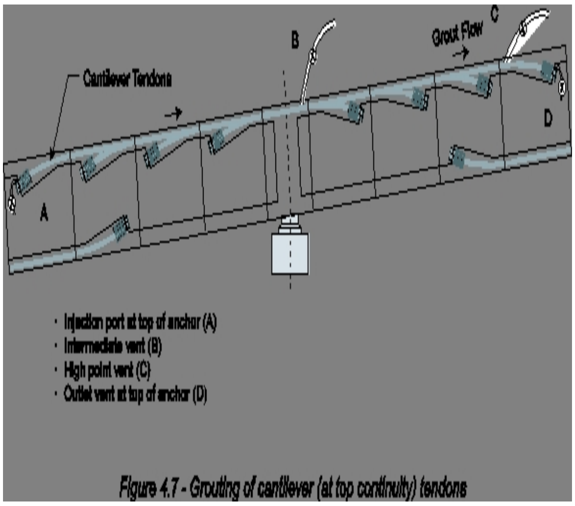


Figure 4.7 - Grouting of cantilever (at top continuity) tendons

- Provide a grout outlet vent at the highest point of the tendon profile (C).
- Provide outlet vent at the end anchor (D).
- If the tendon is longer than 50M (150 ft), provide intermediate vent near mid-length (B).
- Show direction of grouting.
- Sequence of closing vents: B, D, C, A.

4.5.6 Example 6: Bottom Continuity Tendon in Variable Depth Cantilever(Figure 4.8)

- Figure 4.8 illustrates a typical bottom continuity tendon in a structure with variable depth. The following would also apply to a structure of constant depth with anchors in blisters inside the box. Consider duct profile and longitudinal gradient and establish direction of grouting.

- Orient end anchors (A and E) so that grout outlet vents are at top.
- Provide a drainage vent at the lowest point or points (B and D) of the tendon profile allowing for longitudinal grade and tendon configuration.
- Provide grout inlet at B and D. (The drainage vent could also serve as an inlet.)
- Provide an intermediate grout outlet vent (C) at the highest point of the tendon profile or near the mid-length of the tendon if the tendon is longer than 50 M (150 ft).
- Provide another injection port (D) if tendon profile is more than 0.5 M (20 in) lower than intermediate vent (C) and end anchor vent (E).
- Show direction of grouting.
- Sequence of closing vents: A, C, D, E, B.

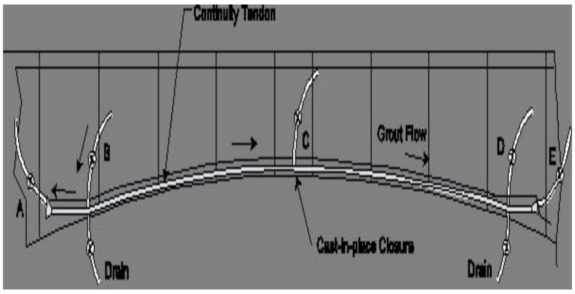


Figure 4.8 - Grouting bottom continuity tendons in variable depth box girders

4.5.7 Example 7: End Span External Tendon in Span-by-Span Structure (Figure 4.9)

Figure 4.9 shows a typical external tendon in the end span of a span-by-span segmental bridge.

- Consider duct profile and longitudinal gradient and establish direction of grouting.
- Orient both end anchors (A and E) so that grout vents are at top.
- Provide grout injection port at low point of tendon profile (B).
- Provide another outlet vent at (C) if the tendon is longer than 50M (150 ft).
- Provide a grout outlet vent (D) at the highest point of the tendon profile.
- Provide another outlet vent at the end anchor (E).
- Show direction of grouting.
- Sequence of closing vents: A, C, E, D, B.

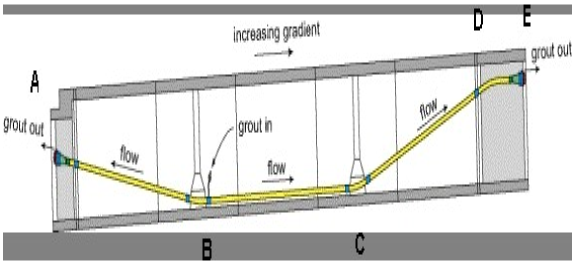


Figure 4.8 - Grouting details for end span, external tendon

Depending upon the details at the pier segments, the tendon may exit horizontally or may curve over and head down to the anchor as shown in Figure 4.10. This requires two different arrangements for the grout outlet vents.

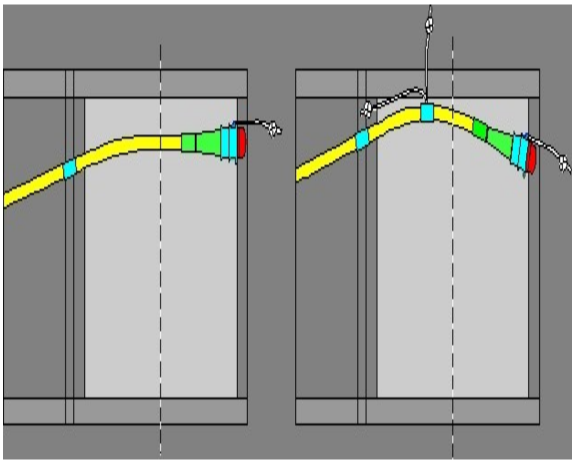


Figure 4.10 - Grouting vent locations at pier segments in span-by-span bridges

4.5.8 Example 8: Inlet and Outlet Connections to Bottom External Tendon:

External tendons typically run along the top of the bottom slab with a small clearance. When it is necessary to provide a drain as well as a grout inlet at the low point of the profile, then the grout tube connections should be located so as to allow the duct to drain. A possible concept is illustrated in Figure 4.11.

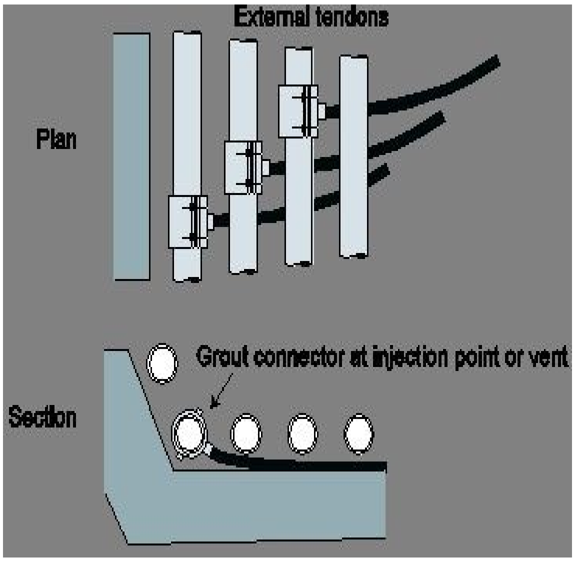


Figure 4.11 - Possible grout and drainage connections for bottom external tendons

4.5.9 Example 9: Lateral Tendons in Hammerhead Pier Cap (Figure 4.12)

- Consider profile and slope and establish the direction of grouting
- Place an outlet at the high point
- Inject from on end of cap
- First close vent at opposite and of cap after evacuating grout
- Vent grout at high point outlet
- Close high point vent, then close inlet

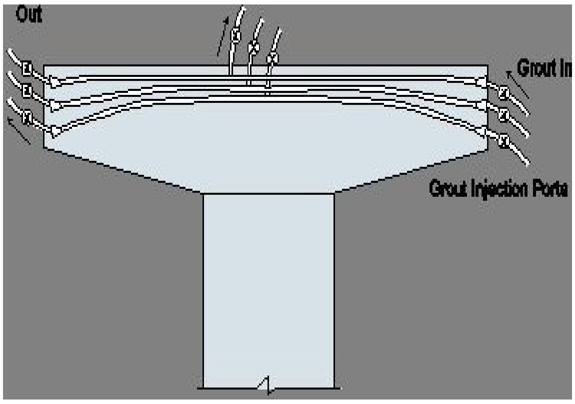


Figure 4.12 - Grouting details for

lateral tendons in hammerhead
piercap

4.5.10 Example 10: Vertical Post-Tensioning in Pier:

Vertical post-tensioning tendons in a pier are illustrated in Figure 4.13.Intermediate grout inlets and outlets are necessary at intervals of no more than approximately 6M (20 ft). This is to facilitate proper filling and, if necessary, staged injection at intervals.

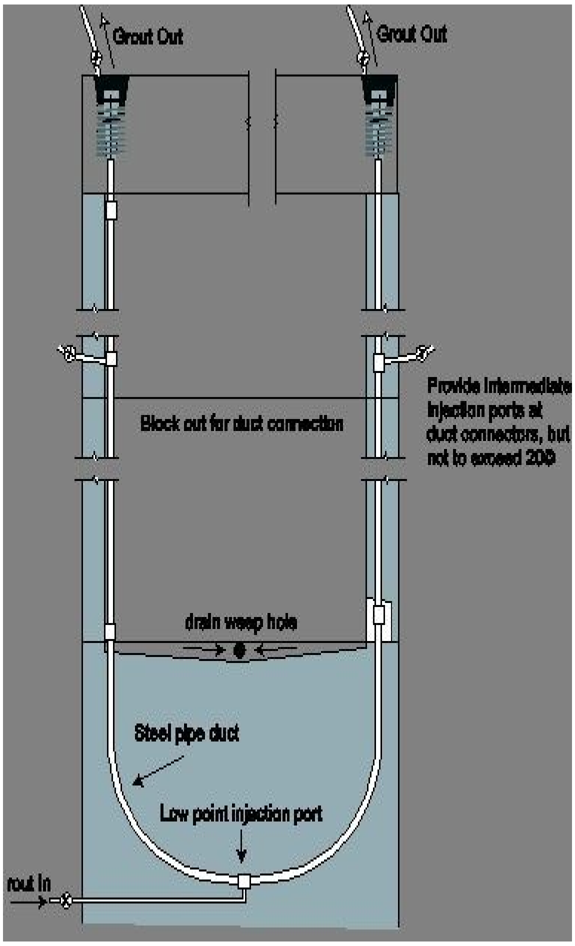


Figure 4.13 - Grouting and anchor
details for vertical tendons in piers

4.5.11 Example 11: Cantilever C-Pier:

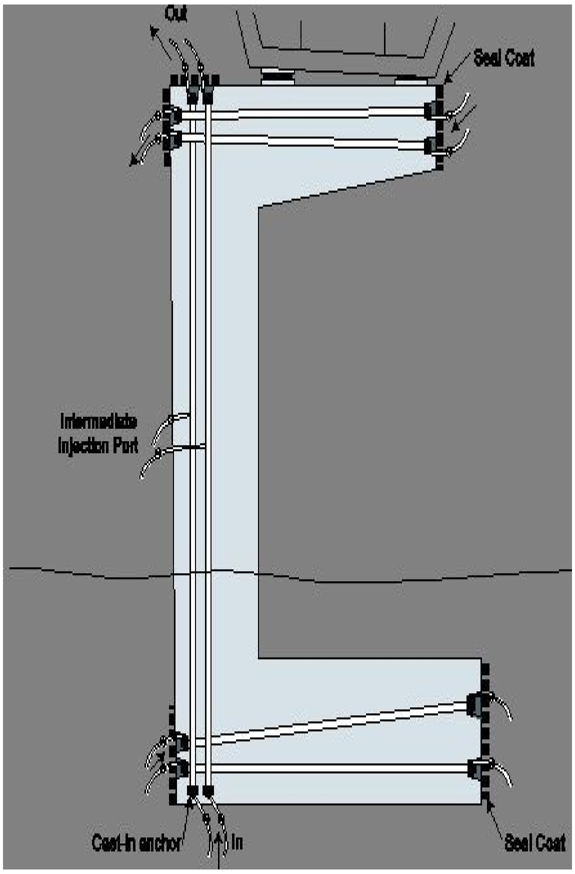


Figure 4.14 - Grouting details details and anchor protection for vertical and lateral tendons in C-pier

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Post-Tensioning Tendon Installation and Grouting Manual

Appendix A - Terminology

Definitions in this manual pertaining to post-tensioned bridges are generally in accordance with the AASHTO Standard Specifications for Highway Bridges, the AASHTO Guide Specifications for Design and Construction of Segmental Concrete Bridges, and the Post -Tensioning Institute Specification for Grouting of Post-Tensioned Structures or similar (State Departments of Transportation) specifications.

A.1 Post-Tensioning Systems

Actual Ultimate Tensile Strength: The actual breaking strength obtained in tests of a single representative strand or bar, breaking outside the anchorage. For multi-strand or bar tendons, AUTS equals the AUTS of a single tendon element (strand, bar) times the number of such elements in the tendon. Representative samples must be from the same coil of strands or the same bar from which strands or bars are cut and used in connection efficiency tests. (Reference PTI "Acceptance Standards for Post Tensioning Systems". See also, "GUTS" and MUTS".)

Anchor nut: The threaded device that screws onto a threaded bar and transfers the force in the bar to the bearing plate.

Anchor plate: That part of the anchorage hardware that bears directly on the concrete and by which the tendon force is transmitted to the structure.

Anchorage: An assembly of various hardware components that secure a tendon at its ends after it has been stressed and imparts the tendon force into the concrete.

Anchorage zone: The general expression for combined general and local zones; see General zone, Local zone.

Anticipated Set: This is that set which was assumed to occur in the design calculation of the post-tensioning forces immediately after load transfer; see Set.

Bar: Post-tensioning bars are high strength steel bars, normally available from 16mm to 44mm (5/8 to 1-3/4in) diameter and usually threaded with very coarse thread.

Basic bearing plate: Flat plate bearing directly against concrete meeting the analytical design requirements. Covered by this definition are square, rectangular, or round plates, sheared or torch cut from readily available steel plate, normally ASTM A 36.

Bearing plate: This is the steel hardware that transfers the tendon force into a structure.

Confinement reinforcement: Non-prestressed reinforcement in the local zone. Confinement reinforcement in the concrete ahead of tendon anchorages is limited to the local zone. Confinement reinforcement consists of spirals, orthogonal reinforcing bars, or a combination of both. For basic bearing plates confinement reinforcement is required in that volume of concrete in which compressive stresses exceed acceptable limits for unreinforced concrete as determined by rational analysis. For special bearing plates, confinement reinforcement is system dependent as determined by tests on individual anchorages. Test block reinforcement, in the portion surrounding the special bearing plate and immediately ahead of it, must represent the confinement reinforcement required in the local zone for that particular system.

Coupler: The means by which the prestressing force may be transmitted from one partial-length prestressing tendon to another.

Duct: Material forming a conduit to accommodate post-tensioned tendon installation and provide an annular space for grout. Post-tensioning ducts consists of spiral-wound corrugated sheet metal, corrugated plastic tubing, metal pipe, or plastic pipe. Post-tensioning ducts are used for external and internal tendons.

Family of Systems: Group of post-tensioning systems for various tendon sizes and unique tendon type with similar tendon components produced by a single supplier.

General zone: The region in which the concentrated prestressing force spreads out to a more linear stress distribution over the cross section of the structural member (Saint Venant Region). It includes the local zone. The general zone extends from the anchorage along the axis of the member for a distance equal to the overall depth of the member. The height of the general zone is equal to the overall depth of the member.

Guaranteed Ultimate Tensile Strength: This is the tensile strength of the material that can be assured by the Manufacturer. GUTS is should not be confused with "f_{PU}" the specified ultimate tensile strength (AASHTO LRFD). (The term "GUTS" has been replaced by two definitions, "MUTS" and "AUTS" by the Post-Tensioning Institute.)

Local zone: The local anchorage zone is the volume of concrete surrounding and immediately ahead of the anchorage device where concrete compressive stresses exceed acceptable values for unconfined concrete (concrete without confinement reinforcement). The local zone is defined as a rectangular prism of concrete surrounding the bearing plate and any integral confinement reinforcement. The transverse dimensions of the prism are equal to those of the bearing plate, including any integral confinement reinforcement, plus the supplier's specified minimum edge covers. The length of the local zone extends over the confinement reinforcement. For anchorage devices with multiple bearing surfaces, the local zone extends over the distance from the loaded concrete surface to the bottom of each bearing surface of the anchorage device plus the maximum dimension of that bearing surface.

Minimum Ultimate Tensile Strength: When measured as a force, for a single strand or bar breaking outside of the anchorage or the multiple of those single strand or bar forces for multi-strand or bar tendons; MUTS is the force equal to the nominal cross-sectional area of strand, or bar, times their nominal ultimate tensile stress. (Reference PTI "Acceptance Standards for Post Tensioning Systems". See Also, AUTS and GUTS.)

Post-Tensioning: The application of a compressive force to the concrete by stressing tendons or bars after the concrete has been cast and cured. The force in the stressed tendons or bars is transferred to the concrete by means of anchorages.

Post-Tensioning Scheme or Layout: The pattern, size and locations of post-tensioning tendons shown by the Engineer of Record on the Contract Plans.

Post-Tensioning System: This is the proprietary system where the necessary hardware (anchorages, wedges, strands, bars, couplers, etc.) is supplied by a particular manufacturer or manufacturers of post-tensioning components and may also include ducts and local zone reinforcement. This may also refer to the stressing equipment.

Prestressing steel: The steel element of a post-tensioning tendon, which is elongated and anchored to provide the necessary permanent prestressing force.

Set: The total movement of a point on the strand just behind the anchoring wedges during load transfer from the jack to the permanent anchorages. Set movement is the sum of slippage of the wedges with respect to the anchorage head and the elastic deformation of the anchor components. For bars, set is the total movement of a point on the bar just behind the anchor nut at transfer and is the sum of slippage of the bar and the elastic deformation of the anchorage components.

Sheathing: General term for the duct material surrounding the prestressing element to provide corrosion protection or conduit for installation.

Special bearing plate: Any hardware that transfers tendon anchor forces into the concrete but does not meet the analytical design requirements. Covered by this definition are devices having single or multiple plane bearing surfaces, and devices combining bearing and wedge plate in once piece. They normally require confinement reinforcement.

Strand: An assembly of several high strength steel wires wound together. Strands usually have six outer wires wound in long-pitch helix around a single straight wire of a similar diameter.

Tendon: A single or group of prestressing elements and their anchorage assemblies, which impart a compressive force to a structural member. Also included are ducts, grouting attachments and grout. The main prestressing element is usually a high strength steel member made up of a number of strands, wires or bars.

Tendon size: The number of individual strands of a certain strand diameter or the diameter of a bar.

Tendon type: The relative location of the tendon to the concrete shape, internal or external and structural function, i.e., draped, cantilever or continuity.

Wedge: Small conically shaped steel components placed around a strand to grip and secure it by wedge action in a tapered hole through a wedge plate.

Wedge Plate: A circular steel component of the anchorage containing a number of tapered holes through which the strands pass and are secured by conical wedges.

Wire: A single, small diameter, high strength steel wire, typically the basic component of strand.

A.2 Post-Tensioning Grout Related Definitions

Admixture: A material, usually a liquid or powder, that is used as an ingredient of the cementitious grout and is added immediately before or during mixing.

Bleed: The autogenous flow of mixing water within or its emergence from, newly placed grout, caused by the settlement of the solid materials within the mass.

Contamination: Any foreign material found in a tendon at any point in time.

Cavitation: Air trapped during the grouting process through an irregular flow of grout through the duct. Cavitation can occur when grouts are injected from high points in the tendon profile or by a poor combination of grouting rate and viscosity, in which the grout traps air as it moves to the low point and does not completely fill the duct.

Final Set: A degree of stiffening of the grout mixture greater than the initial set, indicating the time required for the grout to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test needle.

Fluidity: A measure of time, expressed in seconds necessary for a stated quantity of grout to pass through the orifice of a flow cone.

Grout: A mixture of cementitious materials and water with or without mineral additives or admixtures, proportioned to produce a consistency that may be pumped without segregation of the constituents when injected into the duct to fill the space around the prestressing steel.

Grout Cap: A device which contains the grout and forms a protective cover sealing the post-tensioning steel at the anchorage.

Initial Set: A degree of stiffening of the grout mixture less than the final set, indicating the time required for the grout to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test needle.

Inlet: Tubing or duct used for injection of the grout into the duct.

Outlet: Tubing or duct to allow the escape of air, water, grout and bleed water from the duct.

Permeability to Chloride: A measure of the grout's ability to resist chloride ion penetration.

Potable Water: Water as defined by EPA (Environmental Protection Agency) drinking water standards.

Pressure Rating: The maximum pressure that water in a duct or in a duct component can exert continuously with a high degree of certainty that failure of the duct or duct component will not occur (sometimes referred to as working pressure).

Recharge: The ability of water, outside of the post-tensioning tendon, to migrate through some path and enter the tendon, usually, through the anchorage or at a breach in the duct.

Set Time: The lapsed time for the addition of mixing water to a cementitious mixture until the mixture reaches a specified degree of rigidity as measured by a specific procedure.

Setting: The process, due to the chemical reactions, occurring after the addition of mixing water, which results in a gradual development of rigidity of a cementitious mixture.

Thixotropic: The property of a material that enables it to stiffen in a short time while at rest, but to acquire a lower viscosity when mechanically agitated.

Volume Change: The change in volume produced by continued hydration of cement, exclusive of effects of the applied load and change in thermal or moisture content.

Water-Reducing Admixture: An admixture that either increases the slump of freshly mixed grout without increasing the water content or that maintains the slump with reduced amount of water due to factors other than air entrainment.

A.3 Contract Administration Definitions

Construction Engineering and Inspection (CEI): The person, firm, or organization engaged by the Owner to act as the Owner's representative and be responsible for the overall technical oversight and contract administration to ensure that the project is constructed in accordance with the contract plans, specifications and other contract documents.

Contractor: The person, firm, or organization who enters into a contractual agreement with the Owner to construct the project and who has the prime responsibility for the overall construction of the project in accordance with the contract plans, specifications and other contract documents.

Design-Bid-Build: A process where an Owner engages a designer (Engineer of Record) to produce a complete and final set of Plans, Specifications, Estimates and other Contract Documents to let for open bid by Contractors. The Owner then enters into a contract with the winning or qualified bidder for the construction of the project. The Engineer of Record is independent of the Contractor and may be retained by the Owner to provide reviews or other engineer services during construction.

Design-Build: A process where an Owner invites technical, priced and time scheduled proposals for the complete design and construction of a project to meet an established set of specific, Owner defined, requirements. The Owner then enters into a contractual agreement with the qualifying bidder to design, construct and deliver the completed project in accordance with those requirements. The Engineer of Record (designer) is a member of the Design-Build team.

Engineer of Record: The person, firm, or organization engaged by the Owner to prepare the design, contract plans, specifications or other contract documents for the construction of the project.

Owner: The person, firm, or organization that initiated the design and construction of the project, provides or arranges for funding, is responsible for partial and final payments and who will take possession and ownership of the project upon completion.

Quality Assurance: Actions taken by an Owner or his representative to provide assurance that what is being done and what is being provided are in accordance with the specifications and applicable standards of good practice for the work.

Quality Control: Actions taken by the Contractor to provide control over what is being done and what is being provided to ensure that the specifications and applicable standards of good practice for the work are being followed.

Sub-Contractor: A person, firm, or organization engaged by the Contractor to provide selected construction activities, materials or other specialized construction or engineering services.

A.4 Abbreviations and Acronyms

AASHTO: American Association of State Highway and Transportation Officials (For publications: 444 North Capitol Street, N.W., Suite 249, Washington, DC 20001; www.transportation.org)

API: American Petroleum Institute - (For documents, contact API Publications, Global Engineering Documents, 15 Inverness Way East, M/S C303B, Englewood, Co, 80112-5776, U.S.A., Phone: 303-397-7956, Fax: 303-379-2740, Internet: www.global.ihs.com)

ASBI: American Segmental Bridge Institute - (For documents, contact: American Segmental Bridge Institute, 9201 N. 25th Avenue, Suite 150B, Phoenix, Az., 85021-2721, Phone: 602-997-0064, Fax: 602.997.9965, Internet: www.asbi-assoc.org)

ASTM: American Society for Testing and Materials - (For documents, contact ASTM, 100 Bar Harbor Drive., West Conshohocken, Pa., 19428-2959, U.S.A., Phone: 601-832-9585, Fax: 610-832-9555, Internet http://www.astm.org)

AUTS: Actual Ultimate Tensile

BC: Balanced Cantilever

CIP: Cast-in-Place

CIPBC: Cast-in-Place Balanced Cantilever

EPDM: Ethylene Propylene Deine Monomer (see "External Duct Connections" Chapter 4)

GUTS: Guaranteed Ultimate Tensile Strength.

HDPE: High Density Polyethylene (see "Ducts for Tendons", Chapter 4).

HDPP: High Density Polypropylene (see "Ducts for Tendons", Chapter 4).

I-Girder: A girder (beam), usually precast, typically of a cross-section in the form of an "I" albeit a standard AASHTO I-girder or other section. In the general sense, the term "I-girder" also includes "bulb-T" beams, single and double "T beams", "U-beams" (tubs) and other similar precast or cast-in-place sections. Cast-in-place sections include boxes, slabs and voided slabs that contain post-tensioning tendons.

MUTS: Minimum Ultimate Tensile Strength

PC: Precast

PCBC: Precast Balanced Cantilever

PCSS: Precast Span-by-Span

PT: Post-Tensioning

PTI: Post-Tensioning Institute - (For documents, contact, Post-Tensioning Institute, 8601 North Black Canyon Highway, Suite 103, Phoenix, Arizona 85021, Phone: 602-870-7540, Fax: 602-870-7541, Internet: www.post-tensioning.org)

SS: Span-by-Span

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Post-Tensioning Tendon Installation and Grouting Manual

Appendix C - Further Examples of Post-Tensioning Tendon Applications

C.1 Cantilever Tendons

Cantilever tendons in the top slab of a box section counteract the bending effect from the self-weight of the cantilever during construction. This bending induces a longitudinal tension stress in the top, reaching a maximum over the pier. The top cantilever post-tensioning counters these effects by inducing a compression stress of equal or greater magnitude at each cross section along the cantilever.

Figure C.1 shows a typical layout for cantilever tendons that anchor on the end face of a precast or cast-in-place segment. This feature requires special details to facilitate inspection of the anchor head after tendon grouting and after additional segments have been erected on the cantilever. (A possible detail for a face anchor to facilitate this inspection is shown in Appendix D, Figure D.13).

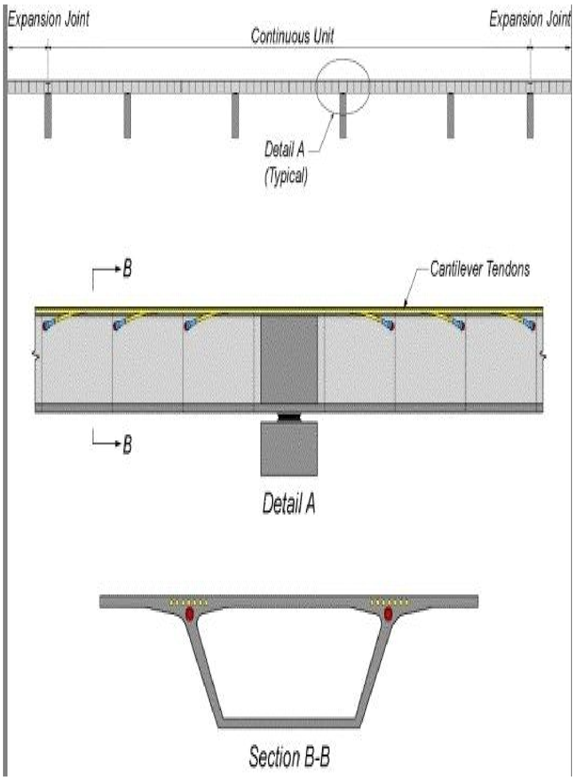

Figure C.1 - Cantilever Post-Tensioning Tendons Anchored on End Faces

An alternate approach is to anchor cantilever tendons in blisters (anchor blocks) cast into the segments at the intersection of the top slab and web (Figure C.2 and Chapter 1, Figure 1.12). Anchorages of these tendons can be inspected at any time during and after construction.

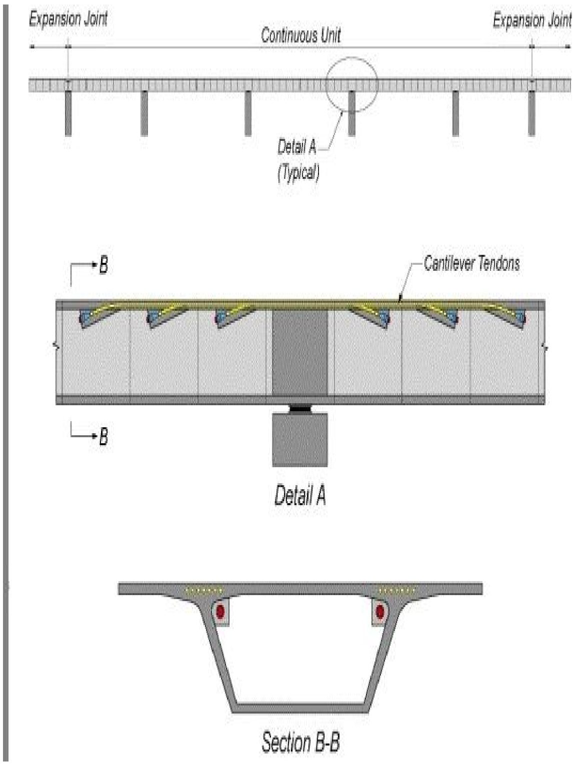

Figure C.2 - Cantilever Post-Tensioning Tendons Anchored in Top Blisters

C.2 Continuity Tendons

To complete a span, the ends of two adjacent cantilevers are connected by a cast-in-place closure pour at or near mid-span of interior spans. In end spans, the closure joint is usually nearer to the end expansion joint. The length of the closure, which comprises the full cross section of the superstructure box, may range from six inches to several feet. In order to align and hold the cantilever tips while making the closure, a special device, referred to as a "closure beam" or "strong-back", is fastened across the tips of the cantilevers. Formwork is secured around the closure, reinforcement and transverse post-tensioning is installed if necessary, and the closure concrete is poured. When the closure concrete attains sufficient strength, longitudinal post-tensioning (continuity) tendons are installed, tensioned and grouted. Figure C.3 depicts typical locations and layouts for bottom continuity tendons at mid-span.

When a closure is several feet long and weighs more than one half as much as a typical segment, it may be necessary to place the closure concrete in a very specific sequence in order to prevent the closure opening or cracking as the cantilevers deflect. It may also be necessary to apply a small amount of post-tensioning (10% to 20% of two continuity tendons) as soon as the bottom slab concrete has taken an initial set (i.e., within about 2 to 4 hours of casting) to keep the closure tight, even as more concrete is added. These are project specific considerations.

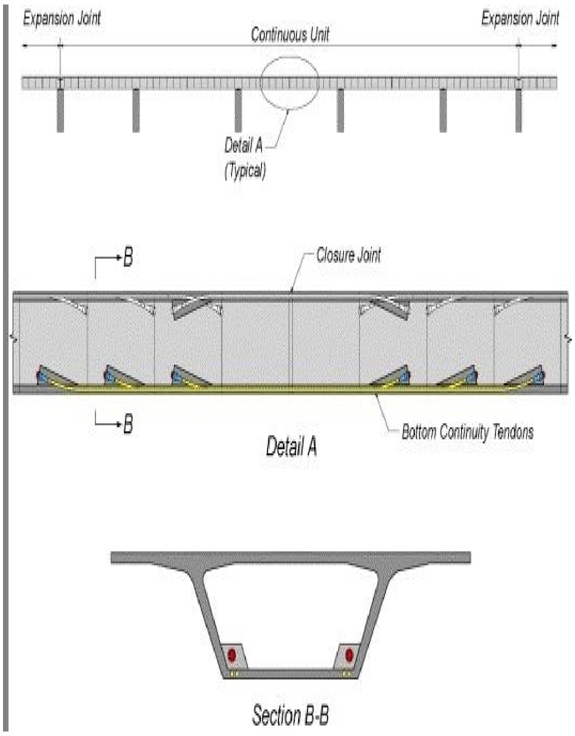

Figure C.3 - Bottom Continuity Tendons for Balanced Cantilever Construction

Top continuity post-tensioning tendons are also typically required in balanced cantilever bridges. A bridge built in balanced cantilever has little, if any, self-weight stress at the location of the closure joint in the center of the span. Midspan bottom continuity tendons, along with live loads in adjacent spans, produce tensile stresses in the top slab that need to be counteracted with top continuity tendons. Subsequent application of the barrier railing and possible wearing surface should produce top compression at this location, minimizing the need for the top continuity tendons. In time, internal redistribution of forces and moments due to the creep of the concrete will induce compression in the top at midspan, further reducing the need for top continuity tendons. Figure C.4 shows details of typical top continuity tendons.

C.3 Continuity Tendons in Expansion Joint Spans

Several segments constructed on falsework are typically needed to complete an end span of a balanced cantilever bridge that terminates at an expansion joint at abutments or expansion piers (Figure C.5). A cast-in-place closure joint connects the cantilever to the segments on falsework and continuity post-tensioning tendons are installed. Usually, more continuity tendons are needed in the bottom than the top. Although continuity tendons may not always be needed in the top, it is good practice to provide at least two, one over each web. Continuity tendons may be stressed from the expansion joint if access is available or they may be stressed at anchor blisters within the superstructure.

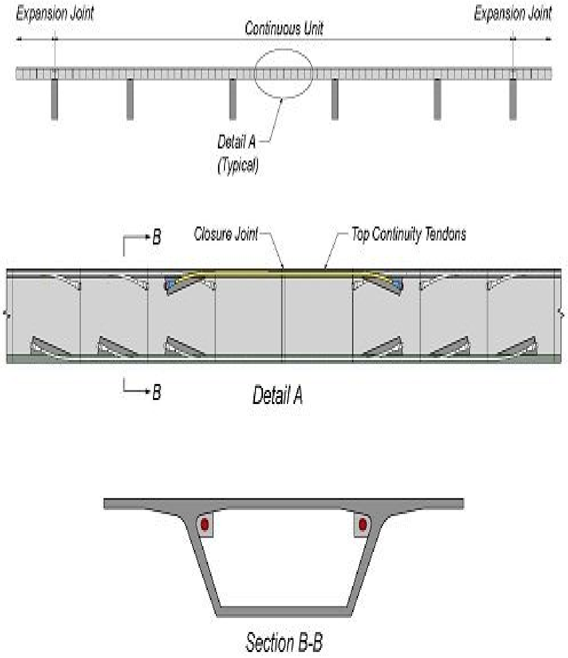

Figure C.4 - Top Continuity Tendons

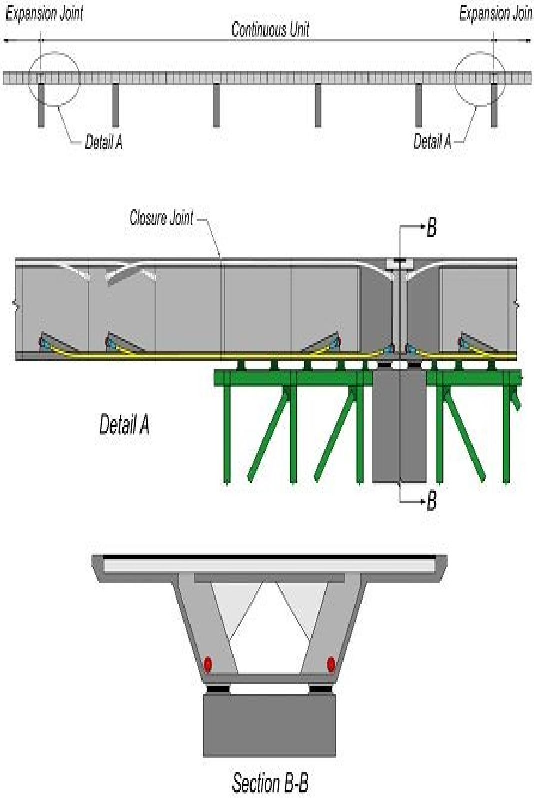

Figure C.5 - Bottom Continuity Tendons near Expansion Joint at a

C.4 In-Span Hinges in Balanced Cantilever Construction

Long viaducts of balanced cantilever construction have been built with dapped-hinges approximately at quarter points of expansion spans (Figure C.6). This location was chosen over the midspan which demonstrated excessive midspan creep deflection in some early generation bridges in Europe and the United States.

Subsequent improvements in long-term creep prediction models for concrete have reduced uncertainties in deflection calculations. Midspan hinges have again been used satisfactorily. Deflection may be controlled by using steel beams on sliding bearings placed inside a box girder, between cantilever tips, to allow for expansion and contraction, but restrain rotation. Care should be exercised in the design and detailing of any type of in-span hinge because local details may be subject to complex force and stress distribution.

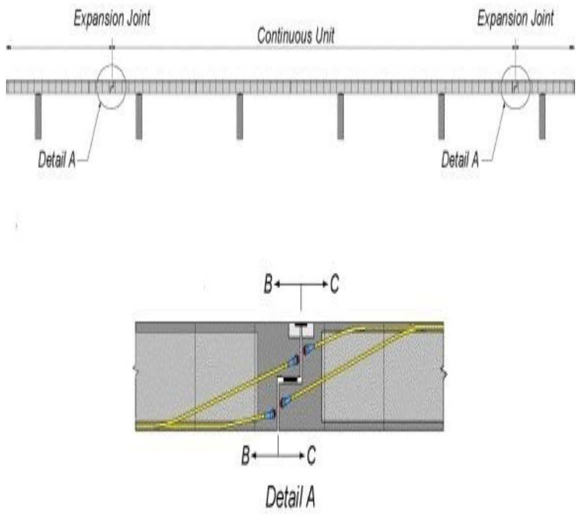

Figure C.6 - In-Span Hinges in Balanced Cantilever Construction

C.5 Precast Segmental Span-by-Span Bridges

For span-by-span construction, the use of external tendons provides for greater efficiency in the cross section of the box for both longitudinal and transverse efficiency, by facilitating a web thicker at the top than bottom. This raises the centroid of the whole cross section, and maximizes the eccentricity and efficiency of the post-tensioning in the mid-span region needed for the dominant effect of longitudinal flexure of this method. Figure 1.15 shows a typical layout of span-by-span tendons for an interior span where all tendons deviate at a common deviation saddle. Figure C.7 shows a similar layout for a typical expansion joint span. Current designs may require an additional (straight) tendon per web to control the effects of thermal gradient and/or provide added redundancy.

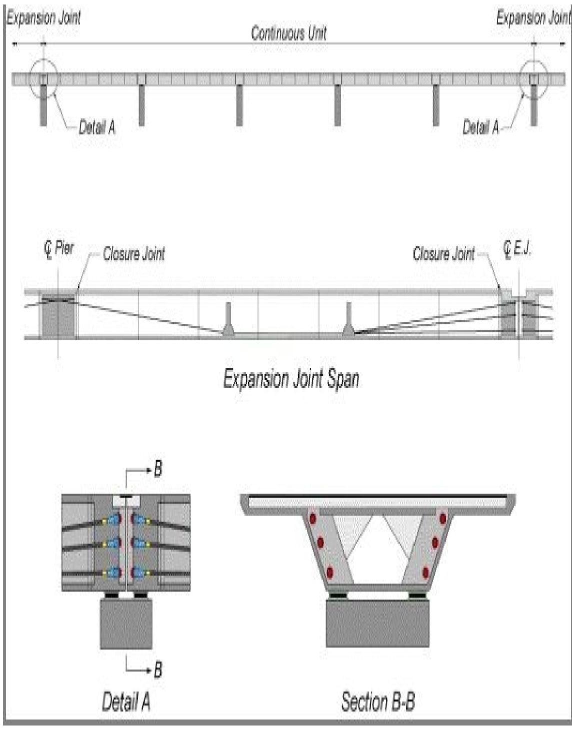

Figure C.7 - Expansion Joint Span Post-Tensioning for Span-By-Span Construction

In some cases, a post-tensioning tendon in a span-by-span bridge may be both external and internal to the concrete. The profile of such a post-tensioning tendon is similar to that of an external tendon except that between the deviators, it enters the bottom slab. The tendon is external in the inclined regions (Figure C.8). This provides additional tendon eccentricity at midspan, but does not facilitate visual maintenance inspection or possible future replacement. However, this type of layout has been used successfully for the Evans Crary Bridge, Florida, and the Central Artery North Area ramps approaches to the Charles River Bridge in Boston. The former was to provide a longer span than normal and the latter, to help address seismic concerns of the time.

With this type of external-internal tendon, Service Limit State conditions are usually readily satisfied. However, at the Strength Limit State, it is necessary to take into account the fact that portions of such tendons are both external (i.e. unbonded) and internal (bonded or partially bonded). An appropriate, non-linear, strain compatibility approach is usually necessary.

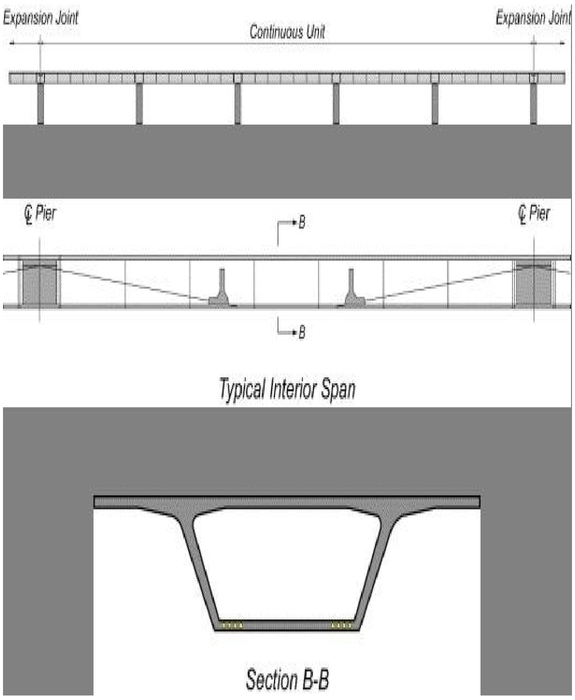

Figure C.8 - External/Internal tendons

C.6 Precast Segmental Progressive Cantilever Bridges

When access to a bridge site is restricted so that precast components can only be delivered to one of the end abutments, the superstructure may be erected in progressive cantilever. Beginning by placing the first span of segments on falsework between the abutment and first pier, subsequent segments are delivered along the completed portion and added in cantilever, progressively to the advancing end. When the cantilever reaches midspan, a temporary support is introduced. More segments are added in cantilever over the temporary support until the advancing end reaches the next permanent pier. This process repeats until the superstructure is completed all the way to the last abutment.

This technique was used to construct the Linn Cove Viaduct carrying the Blue Ridge Parkway around Grandfather Mountain in North Carolina (Figure C.9). Environmental restrictions permitted the use of only walkways and light equipment on the terrain beneath the viaduct. Consequently, equipment and materials for the installation of drilled micro-shaft piles and foundation construction was lowered into each pier location from the advancing end of the cantilever. After completing a footing, precast concrete pier shaft segments were transported along the completed portion of the bridge and lowered into position, building the pier to receive and support the next cantilever.

Figure C.9 - Construction of the Linn Cove Viaduct

The progressive cantilever erection method with changing support conditions requires a complex post-tensioning layout that includes internal cantilever and continuity tendons with draped tendons in the webs. Most tendons were permanent, but a few were temporary and were released as necessary for the changing support conditions.

A similar concept was used by the Federal Highway Administration for the original design of four bridges for the Foothills Parkway in Tennessee (Chapter 1, Figure 1.10). However, with somewhat easier access, under a process that allowed for alternative proposals for construction of the superstructure, the Contractor elected to build them using the cast-in-place balanced cantilever method.

C.7 Transverse Post-Tensioning

Transverse post-tensioning has many uses in concrete bridge construction. Some examples are offered in the following.

C.7.1 Transverse Top Slab Post-Tensioning

Top slabs of precast and cast-in-place segmental, and similar boxes cast-in-place on falsework are often transversely post-tensioned. Transverse post-tensioning typically comprises internal, multi-strand tendons grouted after stressing. Tendons are spaced at regular, frequent intervals, approximately 0.5 to 1.0M (2 to 3 ft), along the structure. Tendons anchor in the block-outs in the edges of the top slab cantilever wings. Blockouts are subsequently filled with concrete and are usually covered with a traffic barrier. Figure C.10 shows a perspective view of typical transverse post-tensioning tendons in a box girder. In precast segments, top slab transverse tendons are usually tensioned and grouted while the segment is in storage in the casting yard.

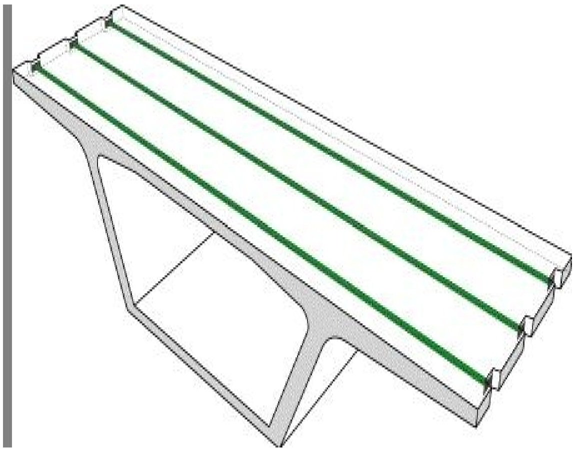

Figure C.10 - Transverse Post-Tensioning in the Top Slab of Box Girder

Wide bridges are often made of twin parallel boxes joined by a longitudinal cast-in-place concrete strip. This closure strip may be conventionally reinforced or transversely post-tensioned. When connected by transverse post-tensioning, only about half of the transverse tendons within a segment are stressed for shipping and erection. The remainder are placed through ducts in adjacent segments and the closure strip and stressed across the full width of the bridge. The latter requires that tolerance be built into the details to accommodate mismatch of the transverse (plan view) alignment due to casting, construction tolerances, differences in elastic shortening, creep and shrinkage between one box and the other. Mismatch of vertical alignment may also occur for similar reasons.

C.7.2 Transverse Post-Tensioning of Multiple Precast Element Superstructures

Short span bridges are often made of multiple precast, prestressed components placed adjacent to one another to form the bridge deck. The precast components include planks for flat slabs, double-tees, and box beams. These bridges may be built with or without toppings. Precast components are often connected transversely with longitudinal closure pours and transverse post-tensioning. High strength bars, mono-strands or multi-strand tendons may be used. The amount of post-tensioning is a function of the specific bridge design requirements.

Suitable allowance should be made for mismatch of tendon alignments due to casting and erection construction tolerances, elastic shortening, creep shrinkage and vertical deflection, in the details for transverse tendons.

C.7.3 Transverse Post-Tensioning in Diaphragms

Superstructure pier segments are occasionally transversely post-tensioned with multi-strand tendons. These tendons may cross each other as they drape from the wing on one side to the opposite face of the web on the other. Often, these transverse tendons extend from web-face to web-face (Figure C.11). These tendons are internal and are usually stressed and grouted in the casting yard.

Proper attention should be given to the details in order to ensure that the tendons are effective at the critical locations. For example, in Figure C.11, the anchors are recessed into the web face and the tendons do not contribute to the resistance of the interface-shear between the web and diaphragm. They contribute only to the transverse tensile force capacity needed across that portion of the diaphragm mostly inboard of the bearings.

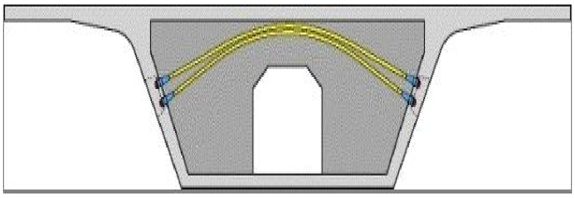

Figure C.11 - Transverse Post-Tensioning in Diaphragms

C.7.4 Vertical Post-Tensioning in Diaphragms

Vertical post-tensioning bars (Figure C.12) are often provided to confine the anchor zones and local splitting effects induced by the concentrated anchorage forces from post-tensioning tendons anchored in groups in the diaphragms of segments. These vertical bars are internal and are stressed and grouted in the casting yard.

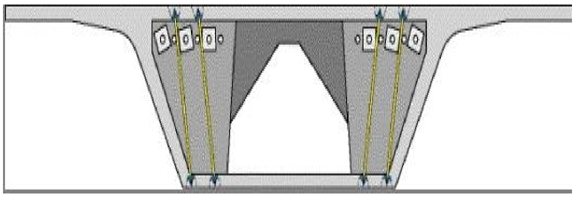

Figure C.12 - Vertical Post-Tensioning in Diaphragms

C.7.5 Vertical Post-Tensioning in Diaphragms

Vertical post-tensioning bars (Figure C.12) are often provided to confine the anchor zones and local splitting effects induced by the concentrated anchorage forces from post-tensioning tendons anchored in groups in the diaphragms of segments. These vertical bars are internal and are stressed and grouted in the casting yard.

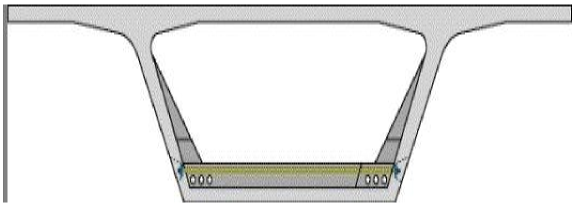

Figure C.13 - Traverse Post-Tensioning in Deviation Ribs

C.7.6 Vertical Post-Tensioning Bars in Webs

Vertical post-tensioning bars are occasionally added to webs (Figure C.14), usually in the high shear zone near the piers, to control principal tension stresses and mitigate or avoid associated cracking. Care should be given to details of the corners to ensure a proper connection and transfer of forces with the top and bottom slab reinforcing.

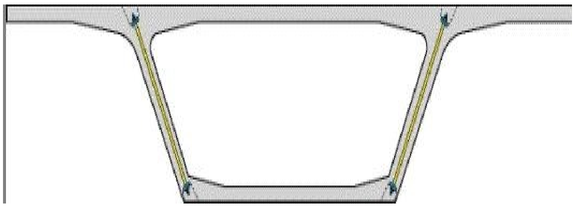

Figure C. 14 - Vertical Post-Tensioning in Webs

Occasionally, in large segments of major segmental or cable-stayed bridges, strand tendons may be used for transverse post-tensioning of webs and diagonal transverse struts or ties that connect and transfer loads to cable-stay anchor points.

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Post-Tensioning Tendon Installation and Grouting Manual

Appendix D - Corrosion Protection of Post-Tensioning Tendons

D.1 Corrosion Protection

Good corrosion protection of post-tensioning is essential for structural integrity and long-term durability. Over the years occasional failures have been detected that were attributed to inadequate grouting and lack of overall protection. The following is an overview of possible methods, materials and details that can help lead to satisfactory corrosion protection.

D.1.1 Background

Originally, in cast-in-place structures and precast structures without intermediate joints, the principle means of corrosion protection was concrete cover. The primary role of grout was to bond the tendon to the surrounding concrete via corrugated ducts, usually made of galvanized steel. Grout was also intended to fill the duct and prevent corrosion from the ingress of contaminants. Unfortunately, many tendons were later found to contain grout voids as a result of incomplete grouting, excess water and bleed. Even though grout did not prevent ingress of contaminants, it was found to surround or coat the post-tensioning steel in an alkaline (passive) environment. Galvanized ducts played a sacrificial role but nevertheless, still allowed occasional corrosion by excess water seeping through seams. Corrosion protection of anchorages was originally achieved by encasement in secondary pours of ordinary structural concrete.

The development of precast segmental construction altered the concept of the corrosion protection as originally perceived for cast-in-place construction. For internal tendons, discontinuities in concrete cover and ducts were to be offset by the use epoxy to seal precast segments at match-cast joints. At joints, both epoxy and grout were intended to provide corrosion protection.

The introduction of external post-tensioning tendons also altered the nature of the corrosion protection system. Concrete cover exists only where tendons pass through deviators, diaphragms and anchor blocks. In between, an external tendon is housed in smooth, high-density, polyethylene pipe filled with grout. Structurally, external tendons are usually considered unbonded - the sole function of grout is to prevent the intrusion of contaminants and surround the steel tendon in an alkaline environment. Polyethylene pipe filled with grout became the principle means of corrosion protection.

While different tendon types evolved with bridge construction methods, there was no significant advance from the original concept of cover and grout for corrosion protection. Recent investigations have exposed several fallacies as regards the assumed roles of various components of such protection. Some are:

- Concrete cover was breached by shrinkage cracks at construction joints and concrete pour-backs at anchor blockouts.
- Corrosion protection of internal tendons was negated by imperfect sealing of epoxy joints in precast segmental bridges - from improper application of epoxy, too aggressive cleaning of the match-cast faces by sand or high-

pressure water blasting, and imperfect duct seals at bulkheads and match-cast segments during casting.

- Grouting procedures created voids due to insufficient filling and use of grout mixes susceptible to bleed water and accumulation of entrapped air.
- Although galvanized ducts offered galvanic protection, discontinuous ducts and imperfectly sealed epoxy joints or duct-splices allowed direct run-off into tendons that were not always fully grouted.
- High-density polyethylene ducts of some external tendons suffered longitudinal splits, allowing moisture direct access to grout or strands. Also, some were damaged due to inspection techniques for determining if grouting had been completed by using a hammer and nail to punch a small hole to check for grout and then not properly repairing the damage.
- Anchor protection by ordinary concrete pour-backs was compromised by shrinkage cracks and leaks in some applications. This was especially problematic for anchors exposed to leaky expansion joints.

D.1.2 Levels of Protection

Corrosion protection of post-tensioning systems can be provided by a number of possible levels according to the system details. Figure D.1 shows six possible levels of protection available for typical post-tensioning tendons in bridge structures. It is recommended good practice to require that at least three of these possible levels are satisfactorily provided from anchor to anchor.

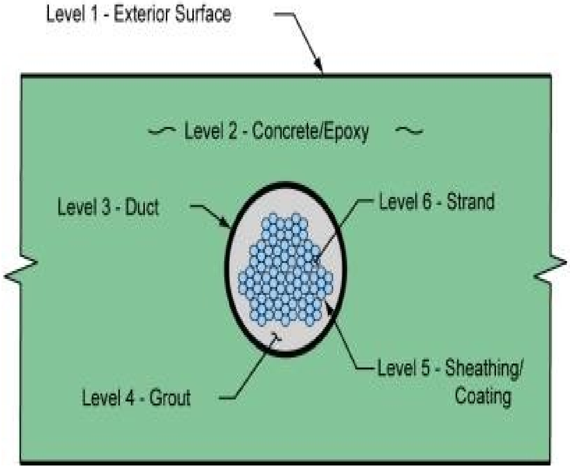

Figure D.1 - Levels of Protection for Corrosion Protection

The six possible levels of protection shown in Figure D.1 are as follows:

- Level 1 - Exterior Surface: The interface between the post-tensioned concrete structure and surrounding atmosphere. Appropriate sealing of surfaces will help keep unwanted contaminants from attacking post-tensioning tendons. Overlays, membranes, and wearing surfaces on bridge decks and sealants applied to other surfaces can provide one level of protection.

- Level 2 - Concrete Cover/ Epoxy: In cast-in-place construction this level is the cover concrete. In precast segmental construction, within a segment between the joints, this level is also cover concrete. At match-cast joints between precast segments this level is properly applied epoxy. For external tendons, inside a box girder but outside of the concrete, this barrier is the entire surrounding box girder structure, providing that it is watertight and well drained. The box provides a benign environment to protect external tendons from physical damage and direct contact with potentially corrosive agents.
- Level 3 - Duct: Cast-in-place construction facilitates either full-length ducts or proper, mechanically, coupled or sealed ducts. For external tendons, durable plastic pipe ducts with sealed connections to steel pipes embedded in deviators and diaphragms can be used. Ducts for internal tendons are typically discontinuous at match-cast joints in precast segmental bridges - special duct couplers have been used on some projects.
- Level 4 - Grout: Good quality is a key ingredient of current tendon protection. Recent research and development of post-tensioning grouts by various state transportation agencies has led to greatly improved grout materials. These grouts have little or no bleed and are available from several sources in pre-bagged, measured quantities for ease of batching and mixing on site. Characteristics and requirements of improved grouts are described in specifications such as the "Specification for Grouting of Post-Tensioned Structures" by the Post-Tensioning Institute. In addition, installation of grout can be improved by engaging personnel trained and qualified in accordance with recognized programs such as the "Grouting Certification Training" of the American Segmental Bridge Institute.
- Level 5 - Sheathing: An opportunity exists to provide corrosion protection between the grout and the strands. Both greased and sheathed mono-strands and epoxy coated (flo-fill) strands are available. There is not a great deal of experience in the placement of these types of sheathed or coated strands either individually or in bundles for large tendons in bridge construction and there is concern that the sheathing or coating may not necessarily remain intact during installation. Current estimates indicate that material cost for epoxy-coated strand is 3.5 times that of bare strand.
- Level 6 - Strand or Bar: The sixth opportunity for protection lies in the main tension element itself. Stainless steel is available for strands or bars, though at considerable expense. The mechanical properties of stainless strand are slightly inferior to normal strand so a given application would require proportionally more strand. Even so, considering the nature of the application, the effort and expense may be warranted. Stainless clad strands are produced in Britain but have not been widely used in the United States. The material cost for solid stainless strand is approximately 10 times, and stainless clad strand 5 times, the cost of bare strand. Carbon fiber strands provide another option for corrosion protection at the level of the main tension element but issues of relatively low modulus of elasticity and, if necessary, possible fire protection may need addressing. There has been little use of any of these materials to date.

D.2 Corrosion Protection Materials

In existing bridges, tendons are typically protected by a combination of three levels: concrete cover, ducts and grout (i.e. levels 2, 3 and 4). Good performance depends on the quality of the individual materials, workmanship, inspection and details.

D.2.1 Concrete Cover

Concrete cover is a primary level of protection. Cast-in-place concrete bridges with infrequent, or no construction joints offer cover protection against free water and contaminants that depends on the quality of the concrete. More frequent construction joints, such as those in cast-in-place balanced cantilever bridges, offer more opportunity for water and contaminants to reach the post-tensioning. Continuity of mild steel reinforcing across construction joints helps maintain the protection afforded by concrete cover. Joints introduced by precast segmental construction methods interrupt the protection offered by the concrete cover alone and therefore must be properly sealed with epoxy.

Cover concrete provides protection to external tendons only where they are embedded in the superstructure at diaphragms and deviators. Elsewhere, external tendons are outside of the concrete and protection is provided by duct, grout and the surrounding box structure.

Cover protection can be enhanced by the use of High Performance Concrete. Also, coatings or sealants can offer further protection.

D.2.2 Ducts

Originally, in post-tensioned bridges, ducts were not considered integral to corrosion protection. Rather, their main purpose was to create the hole through which the tendons would pass. Ducts are now considered as one possible level of corrosion protection.

Different types of ducts offer varying degrees of corrosion protection. Helical wound, galvanized steel ducts provide little physical barrier to the migration of chloride ions through concrete and grout via porous seams. The porosity of this type of duct was considered an advantage in some early research, as it would allow excess water in the grout to be absorbed by the surrounding concrete. In addition, galvanizing offers sacrificial protection.

Plastic ducts provide a physical barrier to the migration of corrosive elements providing that connections are sealed. Plastic ducts for internal tendons can suffer local damage as strands rub and bear against the duct wall during installation and stressing. This is accommodated by requiring a minimum wall thickness.

Ducts for external tendons are made up of alternating lengths of plastic and steel pipe. Plastic pipe is solid extruded, high-density polyethylene (HDPE) with a thick wall. HDPE pipes are connected by elastomeric boots and clamps to steel pipes embedded in diaphragms and deviators. In a closed duct, all water introduced through grouting is either consumed in the hydration of the grout, bleeds through anchor heads or locked inside the duct system. In the free length of external tendons, any grout deficiencies may locally leave the polyethylene duct as the only immediate protection apart from the alkaline environment within the duct from the partial presence of grout. In addition, external tendons are usually protected by being inside a watertight and well drained surrounding box structure.

D.2.3 Grout

Cement grout is chemically alkaline and provides a passive environment around strands. In internal tendons, concrete cover the first level of protection; the duct is the second and grout is the third. In free lengths of external tendons a surrounding watertight and well drained structure is the first level of protection, the HDPE pipe is the second, and grout provides the third by creating an alkaline environment inside the duct.

In all grout applications, hydrostatic head can force excess water in to the interstitial areas between the individual wires of post-tensioning strands and aggravate bleed. Low bleed grout is necessary, and, to maintain adequate levels of corrosion protection, the duct or surrounding concrete must also participate.

D.2.4 Other Considerations

Other considerations and details that influence the whole protection system are, for example:

- Grout inlets and outlets, if not properly sealed, can be a source of ingress.
- Anchor heads can be a point for entry of water or contaminants if the grouting is incomplete. This can be worse at anchors exposed to leaking expansion joints.
- Anchors embedded in or under a deck slab can be susceptible to water ingress through shrinkage cracks around concrete joints or pour-backs.
- Anchors in blisters or at interior diaphragms on the interior of box sections are relatively well protected providing they are completely grouted and are not directly under a leak or where water can pond.
- Grout voids inside anchors that are not tightly sealed can be recharged with humid air or water occasionally laden with salts. As temperatures change humid air can condense inside and possibly aggravate corrosion.

D.3 Corrosion Protection along a Tendon

In normal situations, absent surface sealers, coated strands or exotic strand material, three levels of corrosion protection are provided to tendons according to their type and location, as follows:

D.3.1 Internal Tendons

Internal tendons are protected by; grout, duct and concrete cover (Figure D.2):

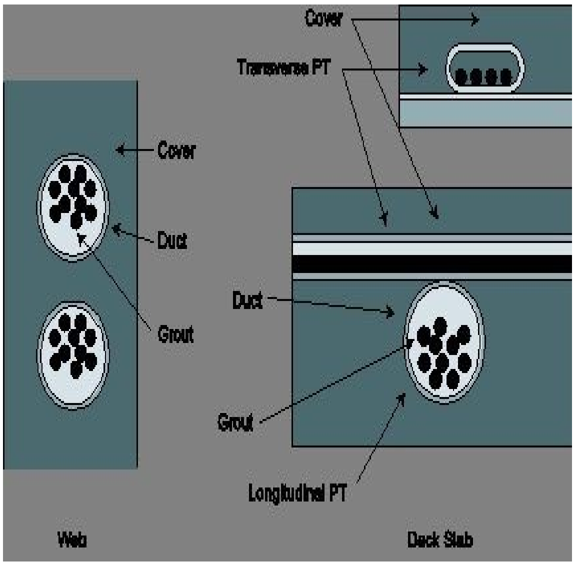

Figure D.2 - Levels of Protection to Internal Tendons

Additional protection to exposed surfaces of girders or webs containing internal tendons may be provided by coatings or sealants. Additional protection to the top surface of a deck slab may be provided by increased concrete cover, waterproofing with protective wearing course overlays, polymer modified concrete overlay or sealers, such as methyl methacrylate (providing that it does not cause bonding issues for wearing surfaces.

D.3.2 External Tendons

External Tendons are protected by grout, duct and the surrounding structure which should be "watertight" and well drained (Figure D.3). In this context "watertight" refers to implementing measures to make sure that cast-in-place splice-joints and joints between match-cast segments are properly sealed and run off leaking through expansion joints is controlled and does not enter an interior hollow box. Drains should be provided through bottom slabs to drain away any water that does enter a box, either from run-off, broken utilities or drainage systems within it.

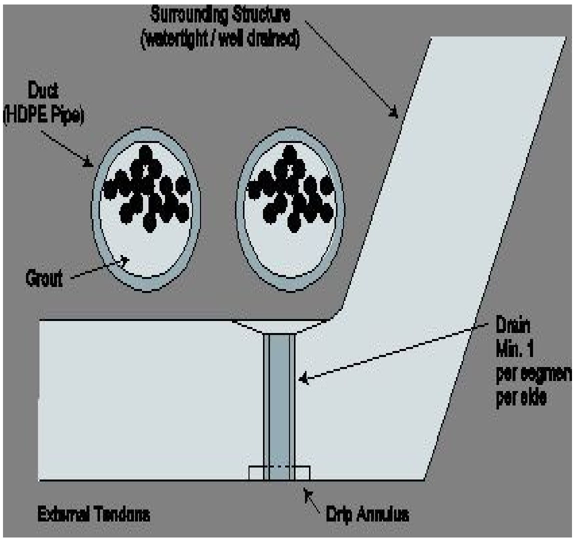

Figure D.3 - Levels of Protection to External Tendons

D.4 Sealing Intermediate Inlets and Outlets

D.4.1 Internal Tendons

It is recommended that intermediate grout inlets and outlets along internal tendon in I-girders and similar components be installed straight to facilitate possible drilling and inspection for complete grout filling using, if necessary, an endoscope. Ends of grout pipes should be sealed with inert (plastic) caps set within a recess. The recess should then be cleaned, roughened and filled with an approved (e.g. epoxy) compound (Figure D.4).

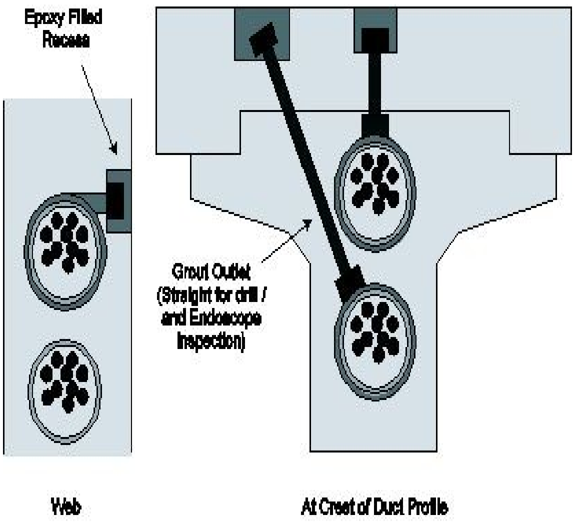

Figure D.4 - Sealing of inlets and outlets internal tendons

D.4.2 External Tendons

It is recommended that grout pipes to intermediate grout inlets or outlets along an external tendon should be neatly trimmed and sealed with an inert, threaded (plastic) cap (Figure D.5). The outlet pipe should be straight to facilitate drilling and inspection with an endoscope, if necessary, to ensure that grout completely fills the tendon.

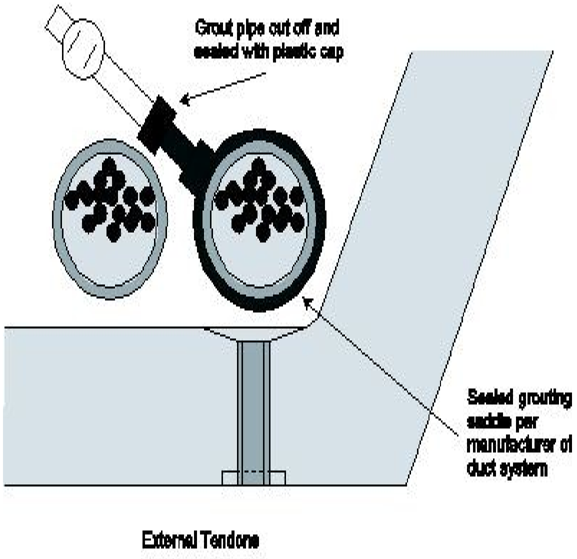

Figure D.5 - Sealing of inlets and outlets along External Tendon

D.5 Corrosion Protection at Anchorages

In some cases, a lack of adequate protection at anchorages led to ingress of water and contaminants resulting in corrosion of post-tensioning. For example, shrinkage and separation of concrete backfill to anchor blockouts in the top slab of some segmental bridges created pathways to anchorages for top internal tendons. Similar shrinkage separation cracks occurred in deck slab pockets left open to access top tendons in concrete I-girder construction. Separation of concrete pour-backs at anchorages under expansion joints, along with incomplete grouting allowed run-off to recharge grout voids and initiate corrosion in a few tendons.

D.5.1 Possible Levels of Anchorage Protection

Measures should be taken to properly protect anchorages. The following are possible means to provide different "levels" of protection. In this context, a level is not necessarily a layer of material, but may also be a step taken to ensure a part of the protection process. It is considered good practice to provide up to "four levels" of anchor protection using combinations of each the following techniques. Each may be considered to provide one possible "level" of protection:

- Grout - a fully filled tendon, anchor and grout cap
- Permanent grout cap of inert (plastic) material
- Concrete pour-back to encapsulate the grout cap and anchor plate
- Full encasement of the end of an I-girder within a reinforced concrete diaphragm
- Encasement of an anchorage under a deck slab along with sealing of construction joints with an approved sealant (e.g. methyl-methacrylate or similar)
- Application of an approved seal coat or sealant to an anchor pour-back
- A surrounding enclosure of a watertight and drained hollow box
- Appropriate application of wearing surface overlays
- Appropriate details at expansion joints to prevent leaks and ingress of water

D.5.2 Permanent Grout Caps

Permanent grout caps of an inert material (an approved plastic or glass reinforced plastic) can provide significant protection to a wedge plate, strand tails and wedges or the nut of a PT bar anchor. The grout cap is filled with grout during tendon grouting, by allowing flow through a special hole in an anchor or wedge plate, through gaps between wedges and interstices of strands. To facilitate filling a grout cap, an opening is needed in the top of the cap. Grout caps should be suitably sealed and secured against anchor plates.

D.5.3 Anchor Protection Details

Subtle distinctions are necessary between, for example, anchorages in the ends of precast beams, under deck slabs or other exposed surfaces. Likewise for anchorages inside a hollow box and relatively remote from direct exposure to corrosive elements as compared to those directly exposed to run-off and windborne salts at expansion joints or similar exposed surfaces. The following descriptions, details and figures are examples to illustrate recommendations for guidance.

General details for anchorages should address proper protection through making sure, as appropriate or necessary, that:

- The correct grout is properly installed to completely fill tendon and anchor.
- Permanent grout cap is fully filled with grout.
- A suitably sized recess is provided, or that there is adequate space to accommodate a pour-back, to completely encase the anchor head and cap.
- Surfaces of recesses and pour-back substrates are thoroughly cleaned and roughened prior to casting pour-backs.
- Anchor and grout-cap are encased in pour-back of an approved, high-strength, high-bond, low-shrink, sand-filled epoxy grout.
- Pour-back provides a minimum cover over cap and edges of anchor plate of 1-1/2 inch.
- For an individual anchor in a recess, surface of pour-back is even with adjacent face of anchor block.
- For a group of anchors, similar individual recesses or a single enclosing pour-back may encase all anchors in the group.
- Single enclosing pour-back is secured to the concrete substrate with embedded reinforcement (e.g. screw coupled rebar) in order to ensure bond.
- Shape and dimensions of single enclosing pour-back is even with adjacent features of structural concrete with chamfers at all outside corners.
- Ends of precast beam-type members are encased in a diaphragm that provides additional (reinforced) concrete over the end of the beam (e.g. Figure D.6) and that at expansion joints, reinforced diaphragms are properly formed and cast. (Only approved joint spacer forming materials (e.g. expanded polystyrene or similar) should be used between continuous units where one diaphragm is cast against the other.)
- The number of anchor block-outs and pour-backs underneath a top deck slab in the ends of beams and spliced-girders is minimized.
- Appropriate and proper use is made of staged construction of spliced-girders (e.g. three-span channel crossings) and similar bridges, so as to be able to install and stress long, full-length, tendons from both (open) approach ends. (This reduces the need to anchor tendons in the tops of girders and also facilitates tensioning.)

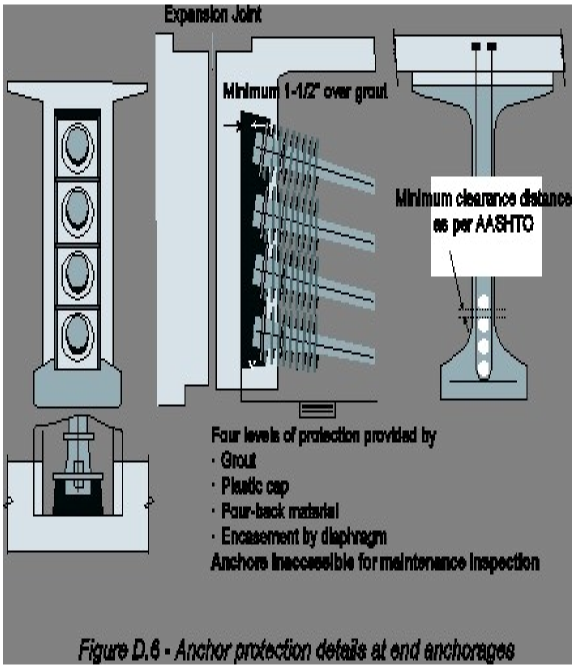

Figure D.6 - Anchor protection details at end anchorages

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- Anchor recesses in the tops of girders and beams are placed in a continuous full-width pour of that portion of the end of the deck slab (Figure D.7) and that the top construction joint is sealed with an approved sealer (e.g. methyl -methacrylate) that does not cause a possible de-bonding issue with any subsequent wearing surface overlay.

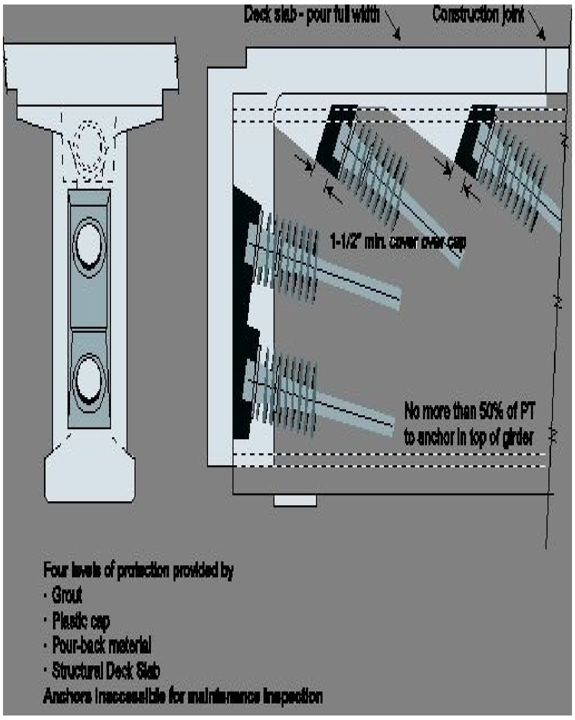

Figure D.7 - Anchor protection details
at top anchorages

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- For an anchor at an interior pier inside a hollow box, an approved seal coat is applied over the cap, over the edge of anchor plate and overlapping onto adjacent structural concrete by a minimum of 12 inches all around the anchor plate or by an additional 6 inches beyond a corner (Figure D.8).
- Box-structures are designed, detailed and built properly to be ventilated, watertight and well drained.
- All finished surfaces of pour-backs and adjacent structural concrete are properly prepared to receive subsequent seal-coats.

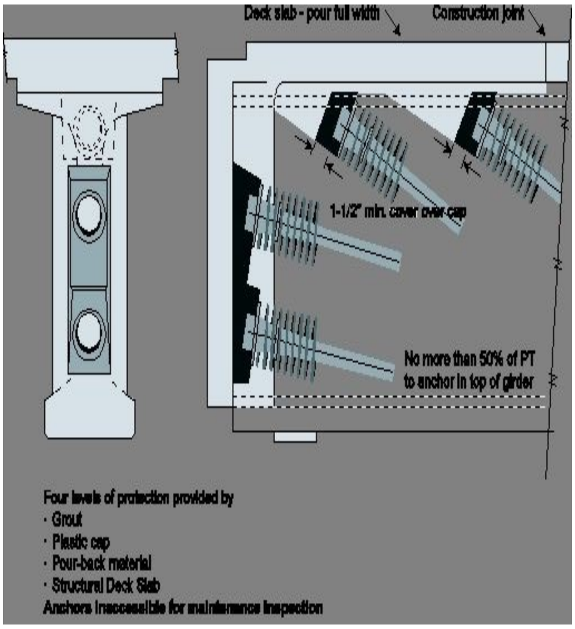

Figure D.8 - Anchor protection at
interior piers

- Longitudinally, anchor blisters are located, preferably, at least 12 in. from transverse construction joints or from joints between precast segments commensurate with (a) the necessary geometry for the tendon path and radius to enter the slab and (b) the minimum length needed for the anchor blister at the (web) location allowing for pie-shaped shortening from any plan curvature. (Figure D.9). (The external shape and size of anchor blisters on the inside of a hollow box should be, as far as possible, the same within a given bridge to facilitate similar rebar details, construction and forming.)
- Anchor blisters are properly reinforced to resist bursting and radial force effects.
- Duct supports are provided for ducts that cannot be directly tied to adjacent rebar.

- A drip groove is recommended in the soffit of the top slab around upper anchor blisters to intercept any possible water path and divert water to the web.
- At expansion joints, anchors are protected from leaking water. A drip flange can provide a positive, protective edge for the top of the seal coat. (Figures D.10, D.11 and D.12)
- In coastal areas, consider adding skirts or baffles over anchor pour-backs at expansion joints to minimize the direct effect of wind borne spray.

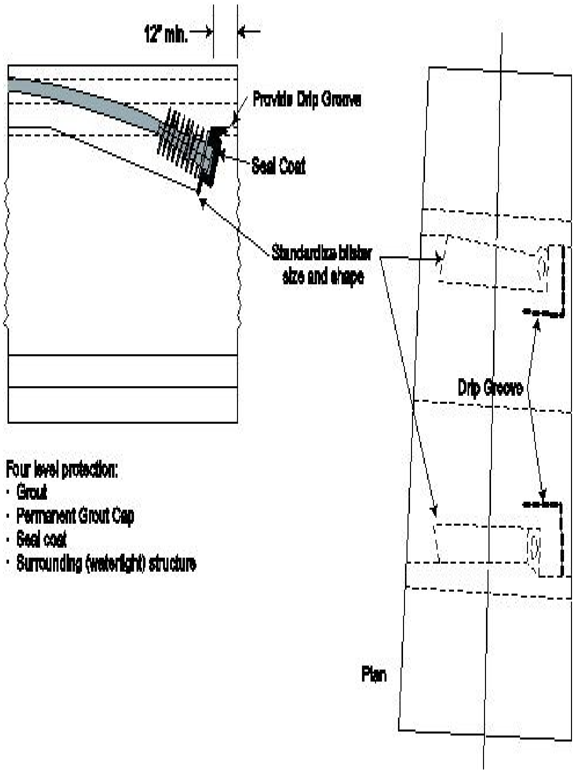

Figure D.9 - Anchor protection for cantilever tendons anchored in blisters

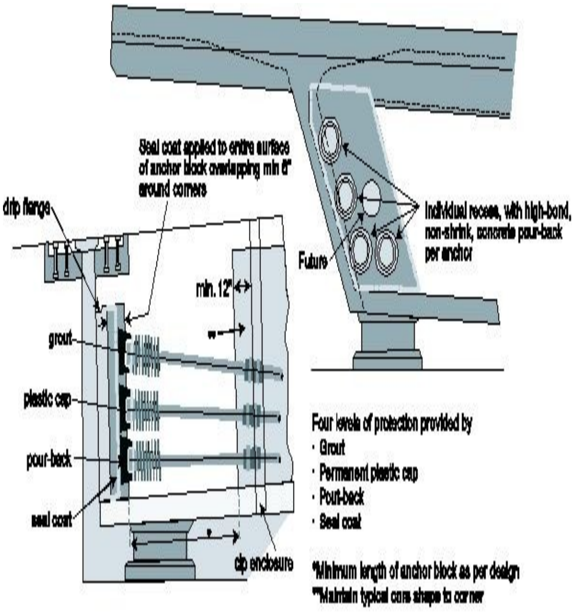

Figure D.10 - Protection of individual anchorages at expansion joints

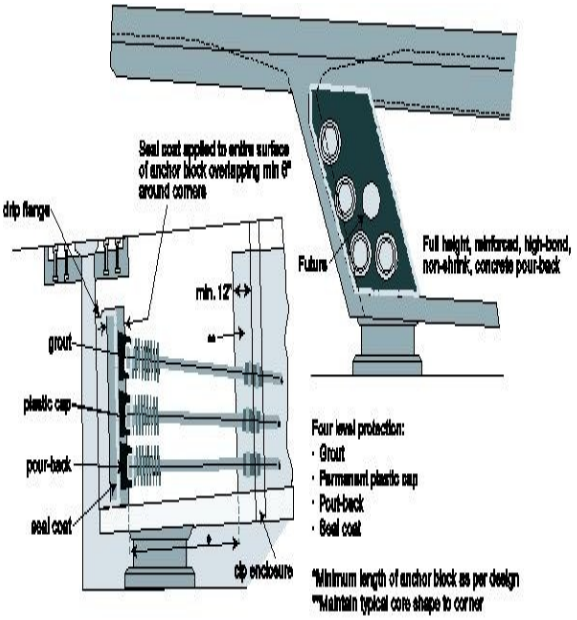

Figure D.11 - Protection of a group of anchors at an expansion joint segment

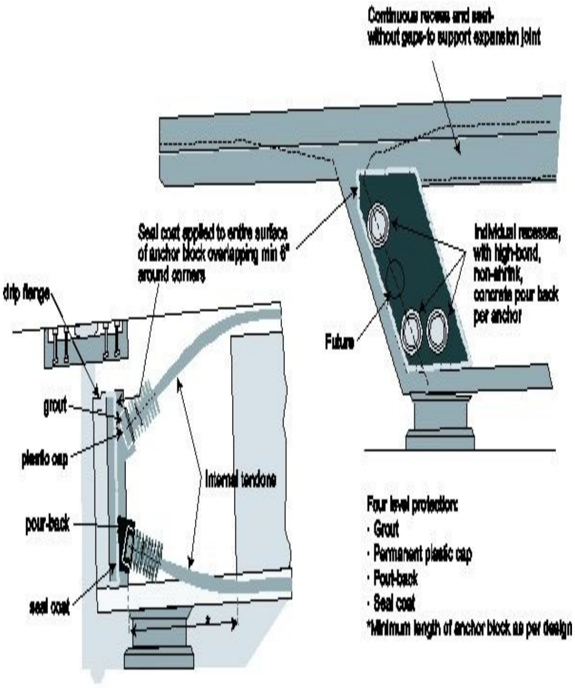

Figure D.12 - Anchorage protection at expansion joints

- Embedded face anchors for top longitudinal tendons in precast or cast-in-place segmental or similar construction should be designed, detailed and installed in such a manner as to provide complete anchor protection in recessed pockets, making use of protection afforded by the grout, permanent grout cap, an approved pour-back material to fully fill the anchor pocket and a sealed joint and / or concrete cover over the pocket (Figure D.13).

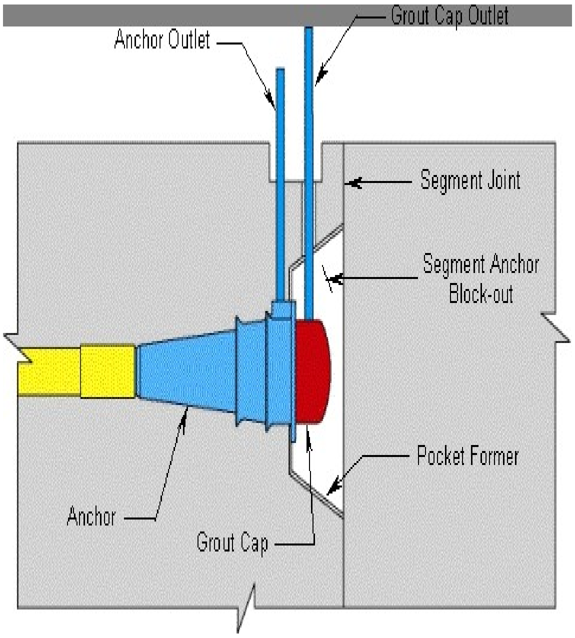

Figure D.13 - Possible Detail for
Embedded Face Anchor

- There should be no permanent openings to any surface (interior or exterior).
- There should be at least 3½ inches of structural (match-cast) concrete cover above any pocket to the top slab riding surface for integrity of concrete and epoxy application.
- Concrete surfaces of an anchor pocket recess should be properly cleaned and prepared prior to placing pour-back material.
- Match-cast joints should be fully sealed with epoxy.
- Grout should be properly installed to completely fill the tendon, anchor and cap.

One possible method for grouting and sealing embedded face anchors includes:

1. Prior to casting, an outlet is installed on the anchor and brought through the top of the concrete surface.
2. An oversized inspection port (approx. 2 inch diameter) is installed through the portion of concrete above the recess and over the grout cap outlet and provide access to the anchor pocket (recess / block-out) created by the pocket former.
3. The concrete segment is then cast.
4. After erection and installation of permanent tendons, but before erection of the next segment, the plastic grout cap is installed on the anchor plate and a vent pipe attached through the oversized port.
5. The tendon is grouted.
6. The anchor and cap are checked to ensure they are full of grout.
7. After grouting the tendon, the anchor outlet may be drilled and inspected for fullness of grout using an endoscope, if necessary. If it is not full, vacuum grouting should be used to fill any void.
8. The grout pipe is trimmed to approximately ½" above base of deck recess. The drilled outlet is then filled from bottom up with epoxy and a cap installed on the grout pipe.
9. The grout pipe on the grout cap is then removed and a plug is inserted into the hole in cap. The oversized access port to the anchor recess below the deck level should be temporarily plugged to keep the recess clean and dry prior to filling with grout.
10. After erection of the next segment and after its tendons have been grouted, the anchor pocket (block-out) is filled to the top of the oversized access port using an approved material such as a high-strength, high-bond, low-shrink, sand-filled epoxy grout or a pre-bagged grout.
11. The grout pipe deck recess is sealed with a sand-filled epoxy grout.

D.5.4 Post-Tensioning Anchorage Protection Installation

It is recommended that permanent protection of post-tensioning anchorages be completed as soon as possible after grouting, preferably within 7 days in aggressive environments or within

28 days in non-aggressive or moderate environments. The type of permanent anchorage protection depends upon the details and location of the anchor as indicated above. General guidance is offered for the following:

D.5.4.1 Surface Preparation

Prior to the application of any new material to a surface, all laitance, grease, coring compound, previous surface treatments, oils or any other deleterious material should be removed by appropriate cleaning, such as wire brushing, grit blasting, water pressure blasting or similar approved techniques, to leave a clean, sound surface without any standing water. When necessary, surfaces should be dried.

D.5.4.2 Forms for Anchorage Pour-Backs

Forms for pour-backs should be leak proof, constructed to neat lines, with a good fit to surfaces in order to withstand pressure from contained material or pumping as necessary. Vents should be provided to allow for the escape of air and complete filling with material as appropriate.

D.5.4.3 Seal Coatings - On Non-Visible Surfaces

Except for anchorages on visually exposed surfaces, (for example, those for transverse tendons in the edges of deck slabs) exposed surfaces of pour-backs or grout caps should be coated with an approved seal coat system. The coating should be mixed and applied in accordance with the manufactures specifications.

D.5.4.4 Concrete Test Block for Seal Coating on Visible Vertical Surfaces

When required by project specifications, a test block with an exposed vertical face at least 2 feet by 4 feet [0.6m by 1.2m] should be prepared to a similar surface texture to the surfaces to be coated on the bridge. The number of coats should be determined to achieve the required coating thickness without runs or drips when mixed and applied in accordance with the manufactures specifications.

D.6 Temporary Protection during Construction

During construction, all post-tensioning ducts and tendons should be temporarily sealed or capped to prevent ingress of water, corrosive agents or site debris and any low point drains should remain open. Particularly:

- Post-tensioning anchors should be sealed at all times to prevent the entrance of water or waterborne contaminants and not blocked with construction debris.
- Temporary caps should be installed as necessary.
- Permanent grout caps should be installed immediately after stressing.
- Inlets and outlets in anchors, grout caps and intermediate grout pipes should be closed with threaded plugs or threaded caps until grouting.
- Plugs and caps should be replaced after grouting but prior to completing permanent anchor protection.

D.7 Watertight Box Girder Bridges

Bridge decks of post-tensioned box girder bridges should be as watertight and well drained as possible, as a "first line of defense" against attack by corrosive agents. Leaks frequently occur through expansion devices and may allow corrosive agents to attack anchors or tendons. Leaks may also occur around temporary openings where fill material shrinks or does not bond. Improperly sealed epoxy-joints between precast box girder segments may also be a source of leaks. The following are suggestions for box structures:

- Seal small diameter holes through deck slabs used for lifting, securing form travelers, construction equipment or other temporary purposes. If possible, tapered holes and provide a drip feature on the underside. Do likewise, for small block-outs.
- Consider use of temporary blisters for temporary PT bars for erection of precast cantilever segments as preferable over using block-outs in top deck slabs.
- Consider minimizing the total number of temporary access manholes through deck slabs that are, nevertheless, often essential to construction and make sure they are properly reinforced and sealed. When sealing concrete joints, use appropriate sealants. (For example, Methyl-Methacrylate may cause bonding issues for wearing surface overlays.)
- At expansion joint devices, avoid the need for temporary openings in or through the seat recess supporting the expansion device. Provide drip notches or flanges to control water flow onto areas containing post-tensioning anchorages.
- In box girders, provided small diameter drains (approx. 50 mm (2in) dia.) through bottom slabs at regular intervals (approximately 3 to 5M (10 to 15 feet)) on low side of box and at all interior barriers and low spots to drain any water that seeps into the box. Provide drip feature to underside of such drains. Provide vermin screens if necessary.
- In hollow columns, consider providing weep holes.

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