



Post-Tensioning Tendon Installation and Grouting Manual



Version 2.0

May 2013

FHWA-NHI-13-026

This Page Intentionally Left Blank.

Technical Report Documentation Page

1. Report No.
FHWA-NHI-13-026
2. Government Accession No.
3. Recipient's Catalog No.
4. Title and Subtitle
Post-Tensioning Tendon Installation and Grouting Manual
5. Report Date
May 2013
6. Performing Organization Code:
7. Author(s)
John Corven, P.E. and Alan Moreton, P.E
8. Performing Organization Report No.
9. Performing Organization on Name and Address
Ideation, Inc.
14150 Parkeast Circle
Chantilly, VA 20151
10. Work Unit No. (TRAIS)
11. Contract or Grant No.
DTFH61-11-D-00026
12. Sponsoring Agency Name and Address
Office of Bridge Technology, HIBT-10
Federal Highway Administration
400 7th Street, SW
Room 3203
Washington, DC 20590
13. Type of Report and Period Covered
Final Document
14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract:

This Manual includes state-of-the-art information relative to materials, post-tensioning systems, construction practices and grouting of post-tensioning tendons for bridges. The Manual is targeted at Federal, State and local transportation departments and private company personnel that may be involved in the design, inspection, construction, or maintenance of bridges that contain post-tensioning tendons. This Manual will serve as a reference and guide to designers, inspectors and construction personnel for post-tensioning materials, installation and a grouting of bridge tendons. The document is part of the Federal Highway Administration's national technology deployment program and may serve as a training manual.

17. Key Words

Bridges, post-tensioning, tendons, grout, grouting, strands, bars, protection, ducts, inlets, outlets, tests, prestressed concrete, pretensioning, stressing, post-tensioning operations, prestressing steel, concrete, bleed.

18. Distribution Statement

This manual can be obtained from the Office of Bridge Technology, Federal Highway Administration, 400 7th Street, SW, Room 3203, Washington, DC 20590.

19. Security Classification (of this report)

Unclassified

20. Security Classification (of this page)

Unclassified

21. No of Pages

184

22. Price

Federal Highway Administration Post-Tensioning Tendon Installation and Grouting Manual

Preface

This Manual includes state-of-the-art information relative to materials, post-tensioning systems, construction practices and grouting of post-tensioning tendons for bridges. The Manual is targeted at Federal, State and local transportation department and private company personnel that may be involved in the design, inspection, construction or maintenance of bridges that contain post-tensioning tendons. This Manual will serve as a reference and guide to designers, inspectors and construction personnel for post-tensioning materials, installation and grouting of bridge tendons. The document is part of the Federal Highway Administration's national technology deployment program and may serve as a training manual.

This Page Intentionally Left Blank.

Table of Contents

Chapter 1 - Introduction	1
1.1 Objective.....	1
1.1.1 Benefits of Post-Tensioning	1
1.1.2 Principle of Prestressing	1
1.1.3 Post-Tensioning Operations.....	2
1.1.4 Post-Tensioning Systems	3
1.2 Permanent Post-Tensioned Applications	6
1.2.1 Cast-in-Place Bridges on Falsework	6
1.2.2 Post-Tensioned AASHTO, Bulb-T, and Spliced Girders.....	6
1.2.3 Precast Segmental Balanced Cantilever Bridges	8
1.2.4 Cast-in-Place Segmental Balanced Cantilever Bridges.....	16
1.2.5 Precast Segmental Span-by-Span Bridges.....	18
1.2.6 Precast Segmental Progressive Cantilever Bridges	21
1.2.7 Transverse Post-Tensioning of Superstructures	22
1.2.8 Post-Tensioning of Substructures	25
1.3 Temporary Longitudinal Post-Tensioning (Bars) – Typical Applications	31
1.3.1 Erection of Precast Cantilever Segments.....	31
1.3.2 Closure of Epoxy Joints in Span-by-Span Erection	33
Chapter 2 – Post-Tensioning System Materials and Components.....	1
2.1 Prestressing Steel.....	1
2.1.1 Strands and Bars	1
2.1.2 Shipping, Handling and Storage.....	3
2.1.3 Acceptance.....	3
2.2 Anchorages and Associated Hardware	5
2.2.1 Anchorages	5
2.2.2 Post-Tensioning Bars Anchor Systems	7
2.2.3 Permanent Grout Caps	8
2.3 Ducts	8
2.3.1 Duct Size	9
2.3.2 Ducts for Tendons	9
2.3.3 Shipping, Handling and Storage of Ducts.....	15

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

2.3.4	Acceptance of Duct Materials	15
2.3.5	Acceptance of Post-Tensioning System.....	15
2.4	Grout.....	16
2.4.1	Purpose	16
2.4.2	Cement and other Pozzolans for Grout.....	16
2.4.3	Admixtures.....	17
2.4.4	Pre-bagged Grouts	17
2.4.5	Thixotropic vs. Non-Thixotropic Grout.....	18
2.4.6	Laboratory Tests.....	18
2.4.7	Shipping, Handling, Storage and Shelf-Life.....	22
2.4.8	Acceptance.....	22
2.4.9	Field Mock-Up Tests.....	23
2.5	Other PT System Qualification Tests	23
Chapter 3 – Post-Tensioning Duct and Tendon Installation.....		1
3.1	Shop Drawings	1
3.1.1	Drawings and Details	1
3.1.2	Stressing Calculations	4
3.2	Tendon Testing On Site	14
3.2.1	Friction.....	14
3.2.2	Modulus of Elasticity	16
3.3	Anchor Installation	17
3.3.1	Anchorage	17
3.3.2	Local Zone Reinforcement.....	17
3.4	Duct Installation	19
3.4.1	Alignment.....	19
3.4.2	Duct Supports.....	23
3.4.3	Splices and Connections	24
3.4.4	Grout Inlets and Outlets	25
3.4.5	Size of Pipes for Grout Inlets, Outlets and Drains	25
3.4.6	Positive Shut-Offs.....	25
3.4.7	Protection of Ducts during Concrete Placement.....	26
3.4.8	Protection of Ducts after Concrete Placement.....	29
3.5	Tendon Installation.....	30

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

3.5.1	Tendon Types.....	30
3.5.2	Proving of Internal Post-Tensioning Ducts	30
3.5.3	Installation Methods.....	30
3.5.4	Aggressive Environments	31
3.5.5	Time to Grouting and Temporary Tendon Protection	32
3.6	Jacks and Other Stressing Equipment	32
3.6.1	Types.....	32
3.6.2	Calibration	35
3.7	Jacking Methods.....	37
3.7.1	Single (Mono) Strand Stressing	37
3.7.2	Multi-Strand	38
3.7.3	Bar Tendons	41
3.8	Stressing Operations	41
3.8.1	Personnel and Safety.....	41
3.8.2	Jacking Force	41
3.8.3	Measuring Elongations on Strand Tendons	42
3.8.4	Measuring Elongations on PT Bars.....	43
3.8.5	Field Variables	43
3.8.6	Final Force.....	45
3.8.7	Strand End Cut-Off	45
3.8.8	Lift-Off.....	45
3.9	Stressing Records.....	46
3.10	Stressing Problems and Solutions	46
3.10.1	Strand Slip	46
3.10.2	Wire Breaks	47
3.10.3	Elongation Problems.....	47
3.10.4	Breaking Wedges	48
Chapter 4 – Grouting of Post-Tensioning Tendons		1
4.1	Grouting Plan.....	1
4.2	Grout Testing.....	2
4.3	Grouting Operations.....	2
4.3.1	Verification of Post-Tensioning Duct System Prior to Grouting.....	2
4.3.2	Grouting Equipment.....	3

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

4.3.3	Batching and Mixing.....	7
4.3.4	On-Site Tests of Production Grout	7
4.3.5	Injection of Grout	9
4.3.6	Grout Injection of Superstructure Tendons.....	9
4.3.7	Grout Injection of Vertical Tendons	10
4.3.8	Post-Grouting Inspection	11
4.3.9	Filling Voids by Vacuum Grouting	12
4.3.10	Sealing of Grout Inlets and Outlets	14
4.3.11	Protection of Post-Tensioning Anchorages	14
4.3.12	Grouting Report	15
4.4	Grouting Problems and Solutions.....	15
4.4.1	Interruption of Grout Flow	15
4.4.2	Too High Grouting Pressure	16
4.4.3	Incomplete Grouting.....	16
4.4.4	Unanticipated Cross-Grouting.....	16
4.4.5	Production Grout Fluidity Unacceptable.....	16
4.5	Examples of Grouting Procedures	16
4.5.1	Example 1: Two-Span Spliced I-Girder (Figure 4.3).....	16
4.5.2	Example 2: Four-Span Spliced I-Girder (Figure 4.4)	17
4.5.3	Example 3: Cantilever and Drop-In Spliced 3-Span I-Girder (Figure 4.5).....	18
4.5.4	Example 4: Cast-in-Place on Falsework (Figure 4.6)	18
4.5.5	Example 5: Cantilever or Top Continuity Post-Tensioning (Figure 4.7)	19
4.5.6	Example 6: Bottom Continuity Tendon in Variable Depth Cantilever (Figure 4.8).....	20
4.5.7	Example 7: End Span External Tendon in Span-by-Span Structure (Figure 4.9).....	20
4.5.8	Example 8: Inlet and Outlet Connections to Bottom External Tendon (Figure 4.11)	21
4.5.9	Example 9: Lateral Tendons in Hammerhead Pier Cap (Figure 4.12)	22
4.5.10	Example 10: Vertical Post-Tensioning in Pier (Figure 4.13)	23
4.5.11	Example 11: Cantilever C-Pier (Figure 4.14).....	24
Chapter 5 – Corrosion Protection of Post-Tensioning Tendons.....		1
5.1	Corrosion Protection	1
5.1.1	Background	1
5.1.2	Corrosion Protection of Post-Tensioning Tendons	2

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

5.1.3	Post-Tensioning System Tendon Protection Levels	4
5.2	Corrosion Protection Materials	4
5.2.1	Concrete Cover	4
5.2.2	Ducts	4
5.2.3	Grout	5
5.2.4	Other Considerations	5
5.3	Corrosion Protection along a Tendon	6
5.3.1	Internal Tendons	6
5.3.2	External Tendons	6
5.4	Sealing Intermediate Inlets and Outlets	7
5.4.1	Internal Tendons	7
5.4.2	External Tendons	8
5.5	Corrosion Protection at Anchorages	8
5.5.1	Anchorage Protection Considerations	9
5.5.2	Permanent Grout Caps	9
5.5.3	Anchor Protection Details	9
5.5.4	Post-Tensioning Anchorage Protection Installation	15
5.6	Temporary Protection during Construction	16
5.7	Watertight Box Girder Bridges	16
Appendix A – Terminology		1
A.1	Post-Tensioning Systems	1
A.2	Post-Tensioning Grout Related Definitions	3
A.3	Contract Administration Definitions	5
A.4	Abbreviations and Acronyms	6
Appendix B – Personnel Qualifications		1
B.1	Contractor’s Personnel	1
B.1.1	Project Engineer	1
B.1.2	Project Superintendent / Manager	1
B.1.3	Foreman	1
B.1.4	Crews for Tendon Installation and Stressing	1
B.1.5	Crews for Tendon Grouting	2
B.2	Construction Engineering and Inspection (CEI)	2
B.2.1	Resident Engineer or Senior Project Engineer	2

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

B.2.2	Project Engineer	2
B.2.3	Lead Inspector	2
B.2.4	Inspector	2
Appendix C – Bibliography		1

Table of Figures

Figure 1.1 - Reinforced Concrete Beam Under Load	1
Figure 1.2 - Comparison of Reinforced and Prestressed Concrete Beams.....	2
Figure 1.3 - Typical Post-Tensioning Anchorage Hardware for Strand Tendons	4
Figure 1.4 - Typical Post-Tensioning Bar System Hardware	4
(Courtesy of Dywidag Systems International).....	4
Figure 1.5 - Typical Post-Tensioning Bar System Hardware	5
(Courtesy of Williams Form Engineering Corporation).....	5
Figure 1.6 - Cast-In-Place Post-Tensioned Construction in California	6
Figure 1.7 - Spliced Haunched I-Girder of Main Span Unit.....	7
Figure 1.8 - Erection Sequence and Temporary Supports for Spliced I-Girder	8
Figure 1.9 - Precast Segmental Balanced Cantilever Construction	9
Figure 1.10 - Typical Balanced Cantilever Segment.....	10
Figure 1.11 - Cantilever Post-Tensioning Tendons Anchored on End Faces.....	11
Figure 1.12 - Cantilever Post-Tensioning Tendons Anchored in Top Blisters	12
Figure 1.13 - Bottom Continuity Tendons for Balanced Cantilever Construction.....	13
Figure 1.14 - Top Continuity Tendons for Balanced Cantilever Construction.....	14
Figure 1.15 - Bottom Continuity Tendons near Expansion Joint at a Support.....	15
Figure 1.16 - In-Span Hinges in Balanced Cantilever Construction	16
Figure 1.17 - Cast-In-Place Segmental Construction using Form Travelers	17
Figure 1.18 - Typical Construction Stages for Cast-In-Place Balanced Cantilever Construction	17
Figure 1.19 - Span-By-Span Construction.....	18
Figure 1.20 - Typical Span Post-Tension for Span-By-Span Construction.....	19
Figure 1.21 - Expansion Joint Span Post-Tensioning for Span-By-Span Construction	20
Figure 1.22 - External/Internal Span-By-Span Tendons	21
Figure 1.23 - Progressive Construction of the Linn Cove Viaduct.....	22
Figure 1.24 - Transverse Post-Tensioning in the Top Slab of Box Girder.....	23
Figure 1.25 - Transverse Post-Tensioning in Diaphragms.....	24
Figure 1.26 - Vertical Post-Tensioning in Diaphragms.....	24
Figure 1.27 - Transverse Post-Tensioning in Deviation Ribs	25
Figure 1.28 - Vertical Post-Tensioning in Webs.....	25
Figure 1.29 - Post-Tensioning in Hammerhead Piers	26
Figure 1.30 - Post-Tensioning in Straddle Bents	27
Figure 1.31 - Post-Tensioning in Cantilever Piers	28
Figure 1.32 - Precast Hollow Segmental Piers, Foothills Bridge No. 2	29
Figure 1.33 - Precast I-Piers	30
Figure 1.34 - Natchez Trace Parkway Arches, Tennessee.....	31
Figure 1.35 - Applying Epoxy between Precast Segments	32
at the Foothills Parkway Bridge No. 2	32
Figure 1.36 - Stressing Temporary Bar in Bottom Slab	32
of the Foothills Parkway Bridge No. 2	32
Figure 2.1 - Basic Bearing Plate Anchorage System.....	5
Figure 2.2 - Multi-Plane Anchorage System (Courtesy of VSL)	6

Figure 2.3 - Anchorage System for Flat Duct Tendon (Courtesy of DSI)	6
Figure 2.4 - Post-Tensioning Bar Anchorage System (Courtesy of DSI).....	7
Figure 2.5 - Permanent Plastic Grout Caps (Courtesy of VSL).....	8
Figure 2.6 - Corrugated Metal Duct.....	10
Figure 2.7 - Corrugated Plastic Duct	11
Figure 2.8 - Grout Vents at Center of a Precast Segmental Pier Segment	12
Figure 2.9 - Duct Coupler for Precast Segmental Internal Tendons.....	13
Figure 2.10 - Duct Couplers in Precast Segmental Construction.....	13
Figure 2.11 - Pressure Distribution: Diabolos vs. Steel Pipe.....	14
Figure 2.12 - Reusable Diabolo Inserts at Deviation Segment	15
Figure 2.13 - Standard and Modified ASTM C939 Flow Cone Testing	19
Figure 2.14 - Wick-Induced Bleed Test	20
Figure 2.15 - Bleed Under Pressure Test (Gelman Filtration Funnel).....	21
Figure 3.1 - Typical Shop Drawing Approval Process for Post-Tensioning	4
Figure 3.2 - Frictional Losses Related to Friction and Wobble.....	5
Figure 3.3 - Four-Span Girder	7
Figure 3.4 - Tendon Geometry	7
Figure 3.5 - Tendon force Diagram for Stressing at End A	9
Figure 3.6 - Tendon Force Diagram after Anchor Set at End A	10
Figure 3.7 - Tendon Force Diagram after Stressing from End B.....	11
Figure 3.8 - Tendon Force Diagram after Anchor Set at End B	11
Figure 3.9 - External Deviated Tendon in End Span	12
Figure 3.10 - Example 2: External Tendon Force after Friction and Anchor Set	13
Figure 3.11 - On-Site Friction Test.....	16
Figure 3.12 - On-Site Bench Test for Modulus of Elasticity.....	17
Figure 3.13 - General and Local Anchor Zone in End of I-Girder.....	18
Figure 3.14 - Local Zone Reinforcing for Edge Anchor in Thin Slab	19
Figure 3.15 - Duct Spacing and Clearance in Post-Tensioned Precast Girders.....	20
Figure 3.16 - Check Longitudinal and Transverse Duct Alignments	21
Figure 3.17 - Anchor Recess and Checking of Duct Alignment	22
Figure 3.18 - Unacceptable Duct Connections and Mistakes	23
Figure 3.19 - Duct Supports in Post-Tensioned Precast I-Girders	24
Figure 3.20 - A Possible Result of Poorly Supported and Connected Ducts.....	25
Figure 3.21 - Connections for Secondary, Vacuum Grouting Operations	26
Figure 3.22 - Excess Wobble Due to Rebar and Duct Conflict	27
Figure 3.23 - Duct Size in Post-Tensioned I-Girders	27
Figure 3.24 - Placing Concrete in Box Segments.....	28
Figure 3.25 - Use of Internal Vibrators for Consolidation of Concrete.....	29
Figure 3.26 - Steel wire sock for installing multi-strand tendon.....	31
Figure 3.27 - Monostrand Jack.....	33
Figure 3.28 - Typical Multi-Strand, Center Hole, Stressing Jack.....	34
Figure 3.29 - Prestressing Bar Jack	35
Figure 3.30 - Jack Calibration	36
Figure 3.31 - Calibration Chart for Pressure Gauge and Jack Force	37

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

Figure 3.32 - Alternate End Stressing	39
Figure 3.33 - Stresses Along Tendon for Different Modes of Stressing	40
Figure 3.34 - Anchor Set or Wedge Set	44
Figure 3.35 - Example Stressing Record Page 1 of 2.....	49
Figure 3.36 - Example Stressing Record Page 2 of 2.....	50
Figure 4.1 - Grout Mixing and Pumping Equipment.....	4
Figure 4.2 - Vacuum Grouting Equipment, Digital Volumeter (up (upper left), Void Volume Measurement (upper right), Grout Pump (lower left), Vacuum Grout injection (lower right) .	6
Figure 4.3 - Grouting Details for a 2-Span Spliced Girder Duct System	17
Figure 4.4 - Grouting Details for a 4-Span Spliced Girder Duct System	17
Figure 4.5 - Grouting Details for a 3-Span, Drop-in and Spliced Girder Duct System	18
Figure 4.6 - Grouting Details for Cellular Box Girder, Voided, or Solid Slab Duct System	19
Figure 4.7 - Grouting of Cantilever Tendons (Top Continuity Tendons Similar).....	19
Figure 4.8 - Grouting Bottom Continuity Tendons in Variable Depth Box Girders.....	20
Figure 4.9 - Grouting details for end span, external tendon	21
Figure 4.10 - Grouting vent locations at pier segments in span-by-span bridges.....	21
Figure 4.11 - Possible Grout and Drainage Connections for Bottom External Tendons.....	22
Figure 4.12 - Grouting Details for Lateral Tendons in Hammerhead Pier Cap.....	22
Figure 4.13 - Grouting Details for Vertical Tendons in Piers	23
Figure 4.14 - Grouting Details and Anchor Protection for Vertical and Lateral Tendons in C-Pier	24
Figure 5.1 – Levels of Protection for Corrosion Protection	2
Figure 5.2 – Levels of Protection to Internal Tendons	6
Figure 5.3 – Levels of Protection to External Tendons	7
Figure 5.4 – Sealing of Inlets and Outlets along Internal Tendons	8
Figure 5.5 – Sealing of Inlets and Outlets along External Tendons	8
Figure 5.6 – Anchor Protection Details at End Anchorages	10
Figure 5.7 – Anchor Protection Details at Top Anchorages	11
Figure 5.8 – Anchor Protection at Interior Piers.....	12
Figure 5.9 – Anchorage Protection for Cantilever Tendons Anchored in Blisters.....	13
Figure 5.10 – Protection of Anchorages at Expansion Joints.....	13
Figure 5.11 – Possible Detail for Embedded Face Anchor	14

Table of Tables

Table 3.1 - Example 1 Tendon Force and Elongation Calculation	8
Table 3.2 - Example 2 Tendon Force and Elongation Calculation	13

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 design, installation, grouting and inspection of post-tensioning tendons for prestressed concrete bridges.

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. Reinforcing steel can be embedded in the concrete members to accept tensile stresses which plain concrete cannot resist. 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 members may crack, but it can effectively carry the design loads (Figure 1.1).

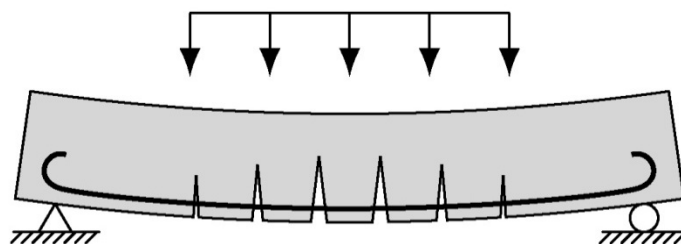


Figure 1.1 - Reinforced Concrete Beam Under Load

Although cracks occur in reinforced concrete, the cracks are normally very small and well distributed. 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 applied loads 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 post-tensioning 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 under the action of post-tensioning and applied loads. 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 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. As a result, durability is increased and more efficient, cost effective construction is realized.

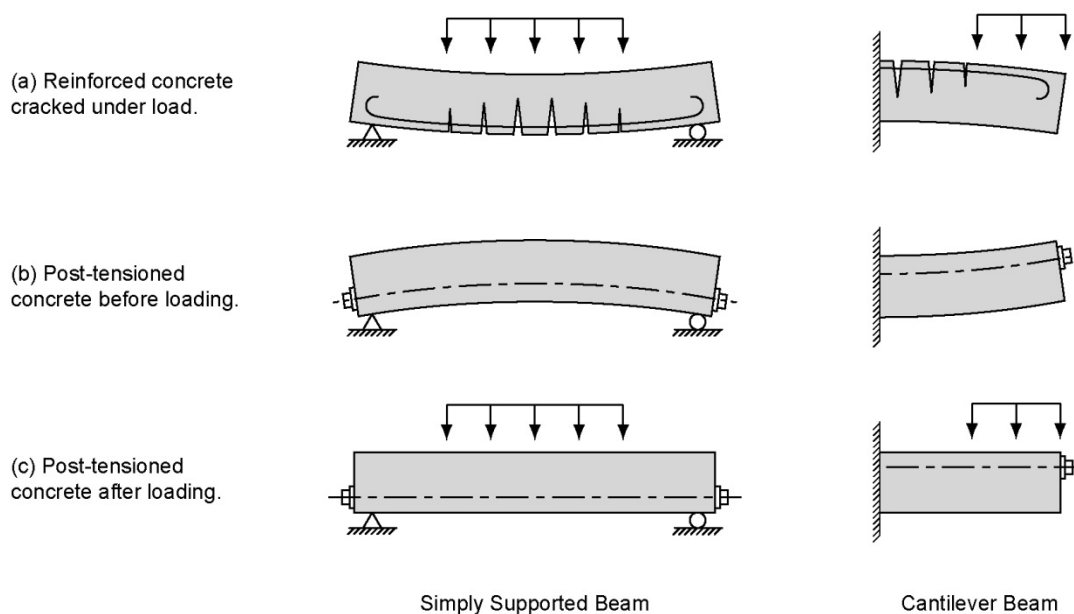


Figure 1.2 - Comparison of Reinforced and Prestressed Concrete Beams

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 after the concrete has been placed, hardened and attained a minimum compressive strength for that transfer.

1.1.3 Post-Tensioning Operations

Compressive forces are induced in a concrete structure by tensioning steel tendons comprised 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 anchored 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.

The protruding “tails” of strands or bars of permanent tendons are cut off using an abrasive disc saw or plasma cutting after stressing. Flame cutting should not be used as it negatively affects the characteristics of the prestressing steel. 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. After grouting, anchorages are protected by multiple levels of protection appropriate to the environmental demand on the structure. See Chapter 5 for details regarding corrosion protection of tendons.

Materials other than cementitious grout, such as wax, have been used to fill ducts after the installation and stressing of tendons. These materials are not commonly used in the United States and are not addressed in this Manual. Post-tensioning and grouting operations require certain levels of experience and certification, 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 multi-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.

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

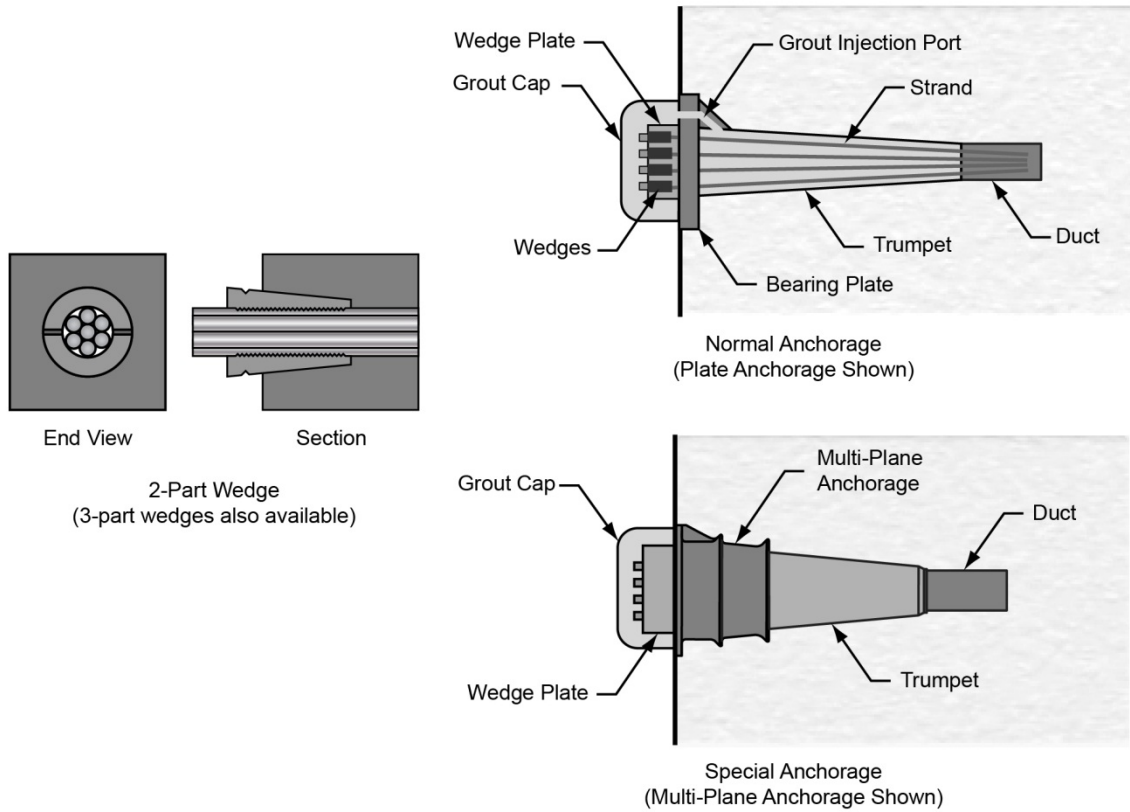


Figure 1.3 - Typical Post-Tensioning Anchorage Hardware for Strand Tendons

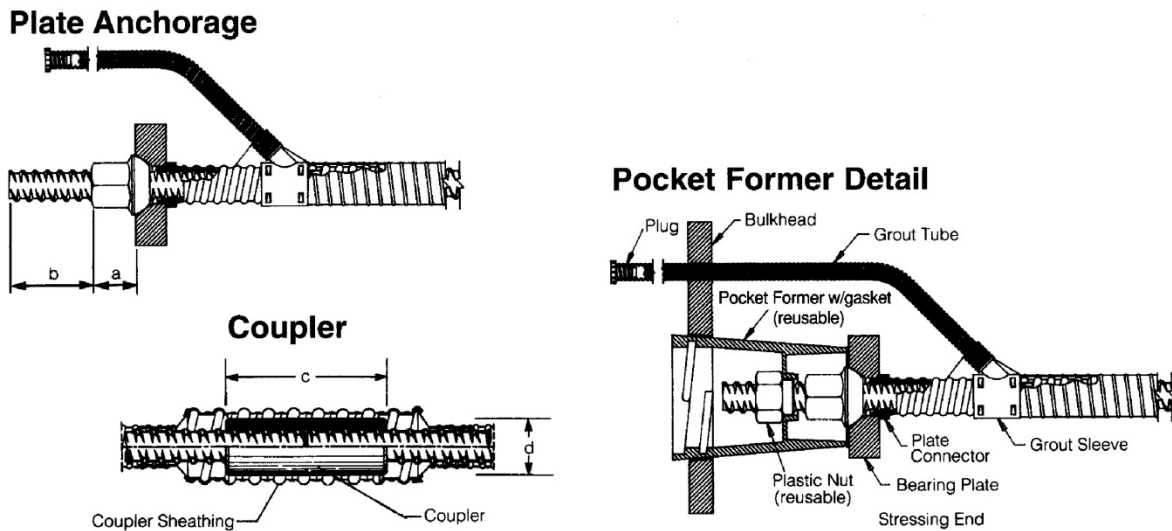
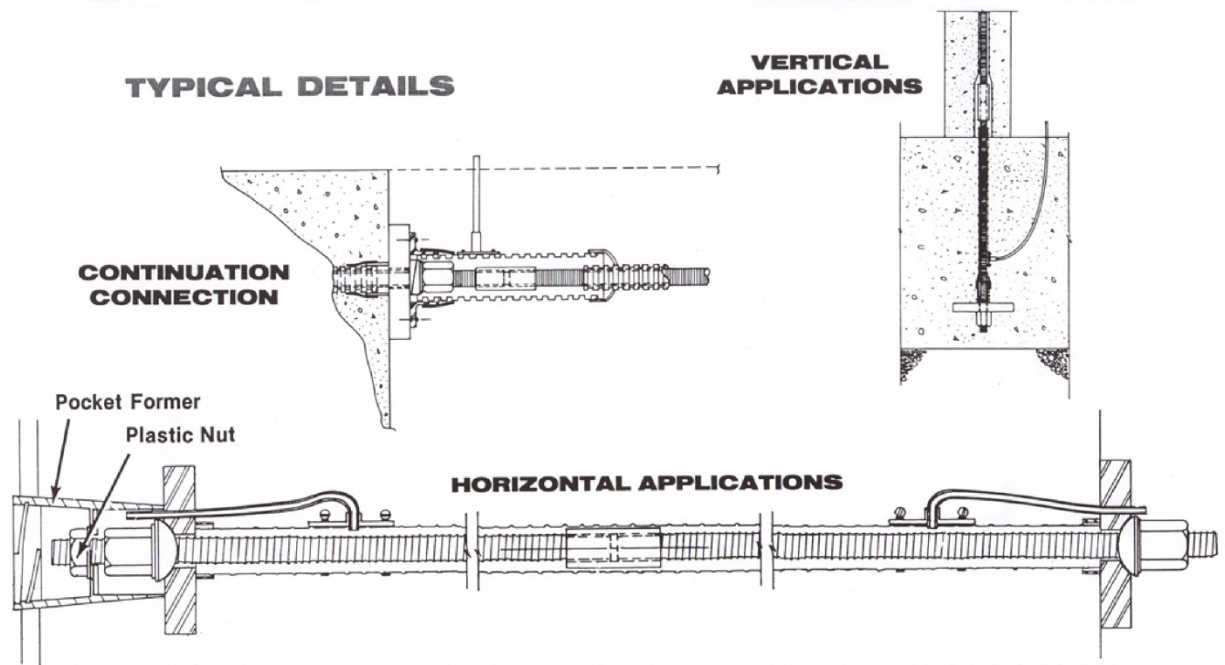


Figure 1.4 - Typical Post-Tensioning Bar System Hardware
 (Courtesy of Dywidag Systems International)



*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 draped along the length of the girder to a designed profile. In continuous spans, the tendon profile lies in the bottom of the girder 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. The girder segments are made continuous over multiple spans (typically three or four spans) by cast-in-place joints that connect the girder ends and are incorporated as a part of transverse diaphragms at the piers.

Post-tensioning ducts that are cast into the webs are spliced at 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

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

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 Span Unit

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 segments 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.

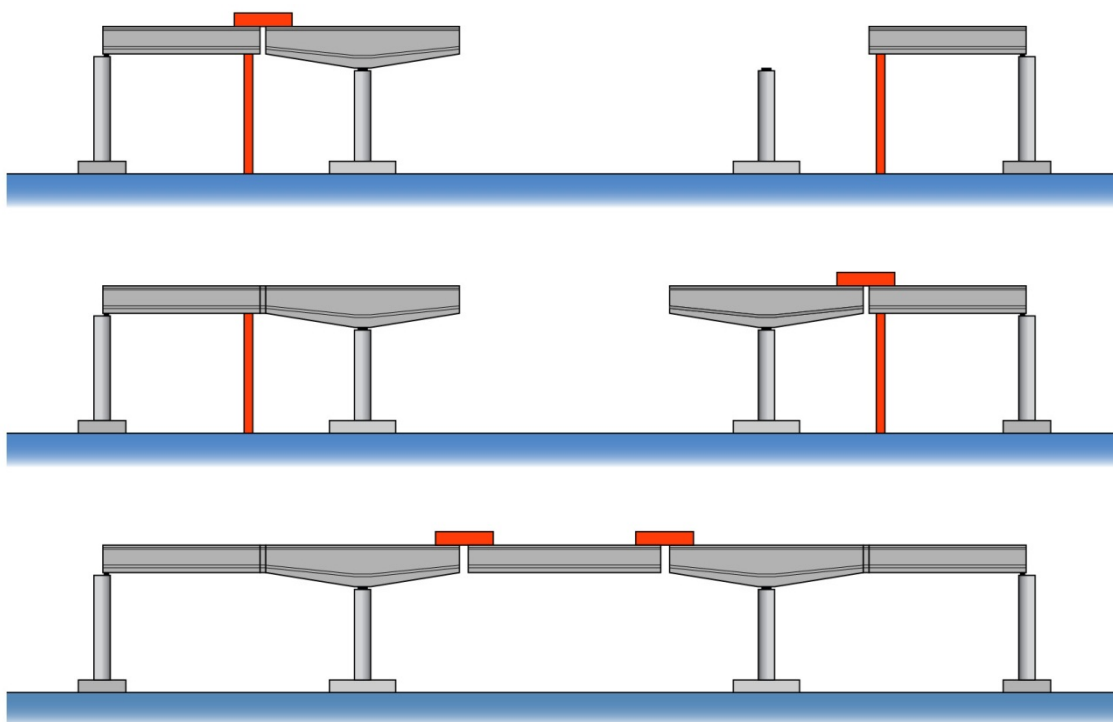


Figure 1.8 - Erection Sequence and Temporary Supports for Spliced I-Girder

1.2.3 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.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Figure 1.9 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 into continuous spans. Other methods of erecting the precast segments are available, including deck mounted beam and winch systems and tire mounted segment lifters.

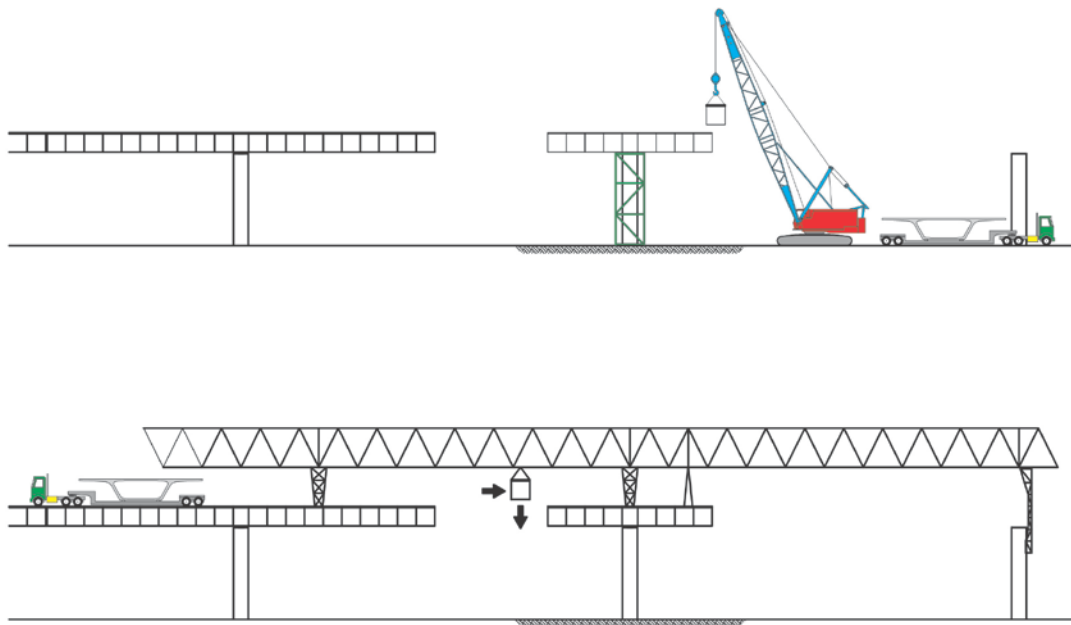


Figure 1.9 - Precast Segmental Balanced Cantilever Construction

1.2.3.1 Typical Features of Precast Cantilever Segments

Figure 1.10 presents a perspective of a typical balanced cantilever segment showing various features of the concrete shapes, post-tensioning tendon locations and post-tensioning anchorage locations. The principal types of post-tensioning tendons in these bridges are cantilever and continuity tendons. The cantilever tendons are stressed to resist the cantilever dead load moments during construction and the effects of superimposed dead loads and live loads on the continuous bridge. Continuity tendons are stressed to join adjacent cantilevers and resist positive moments from superimposed dead loads, creep redistribution, and live loads.

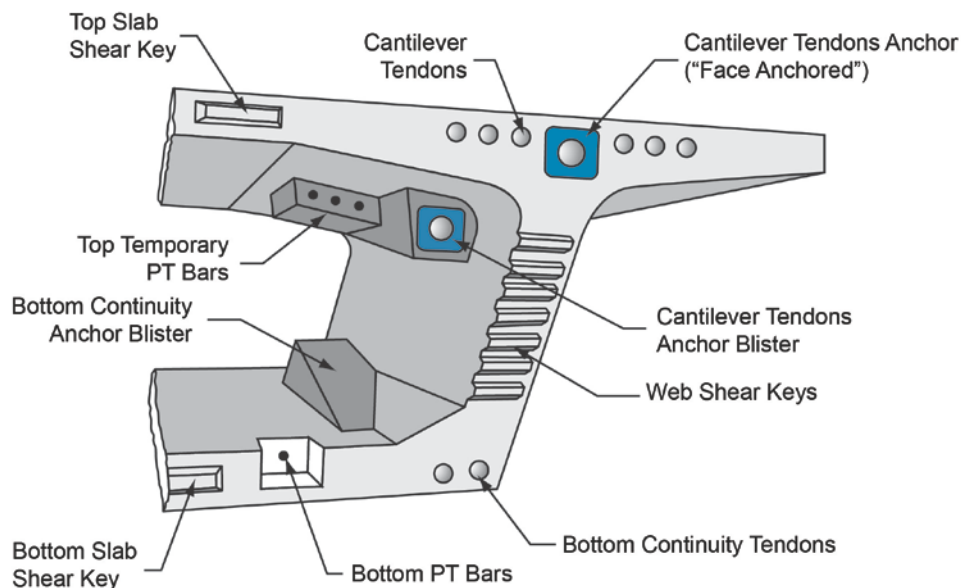


Figure 1.10 - Typical Balanced Cantilever Segment

1.2.3.2 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 of the ducts is always the same at each side of the 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. 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.

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.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Figure 1.11 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 Chapter 5, Figure 5.11).

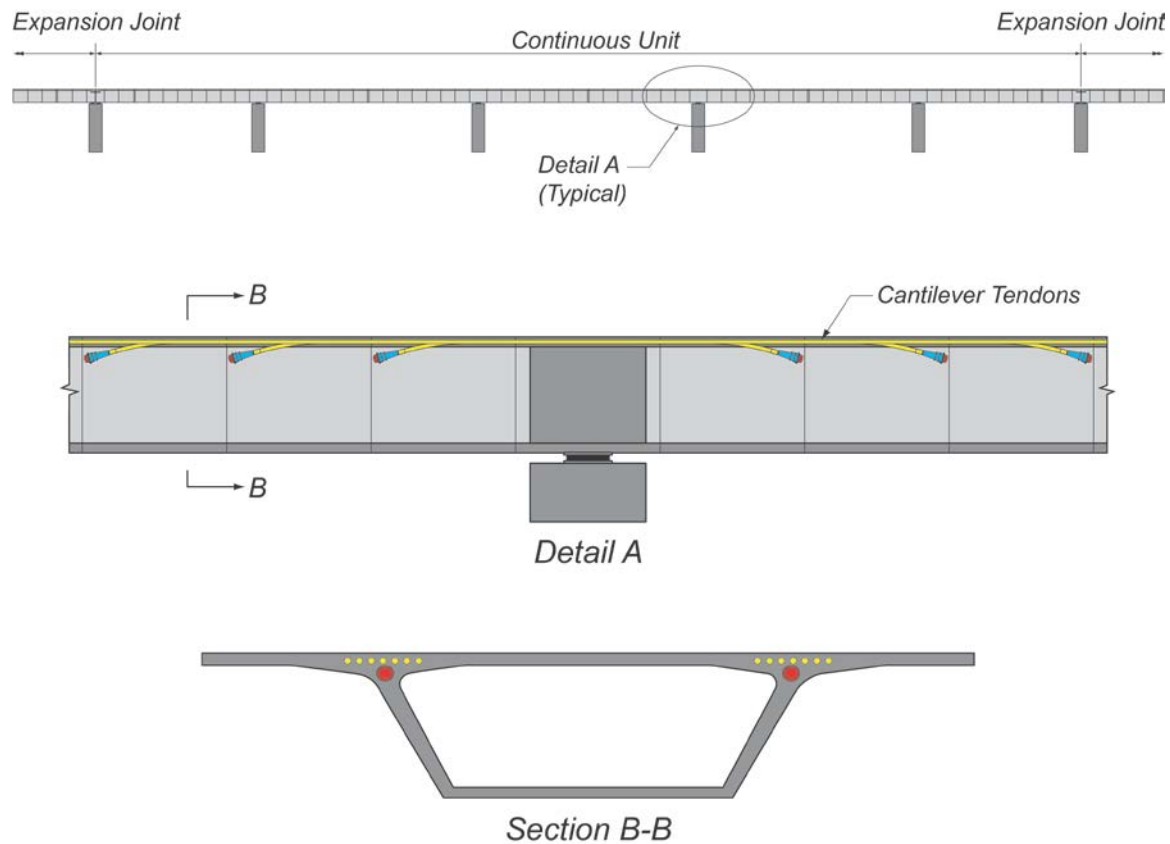


Figure 1.11 - Cantilever Post-Tensioning Tendons Anchored on End Faces

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 as shown in Figure 1.12. Anchorages of these tendons can be inspected at any time during and after construction.

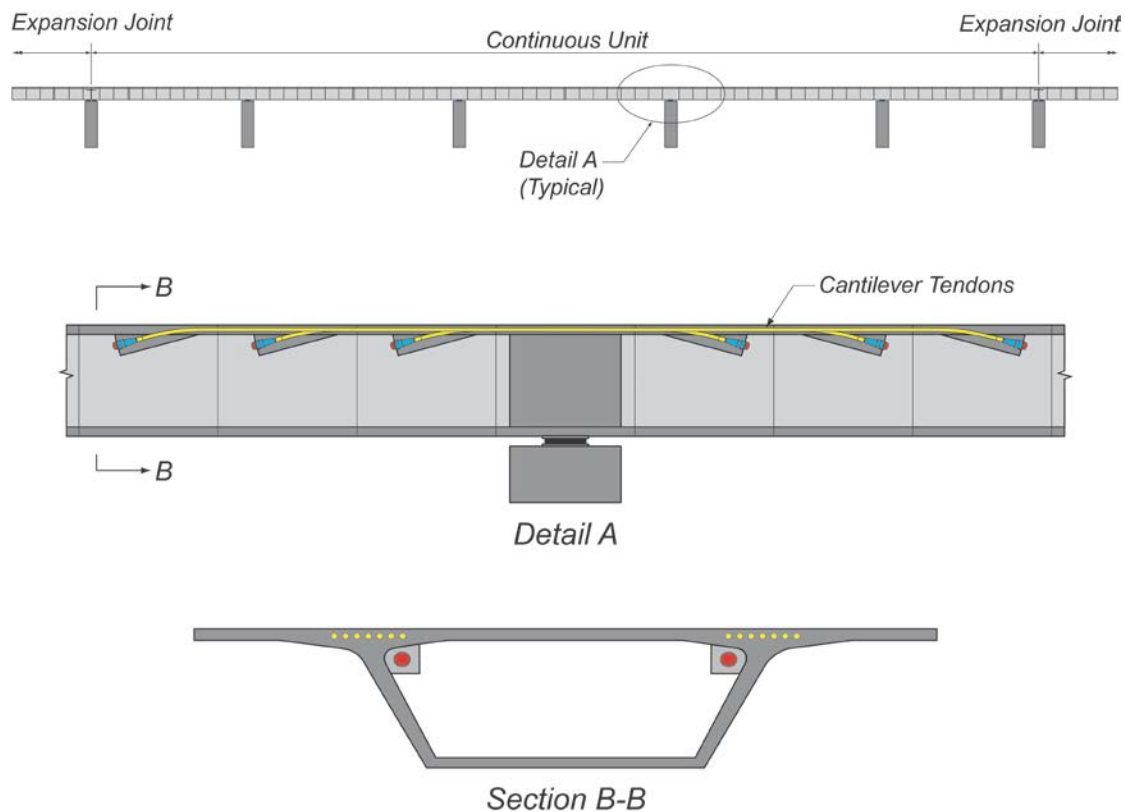


Figure 1.12 - Cantilever Post-Tensioning Tendons Anchored in Top Blisters

1.2.3.3 Continuity Tendons between Cantilevers

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 1.13 depicts typical locations and layouts for bottom continuity tendons at mid-span.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

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.

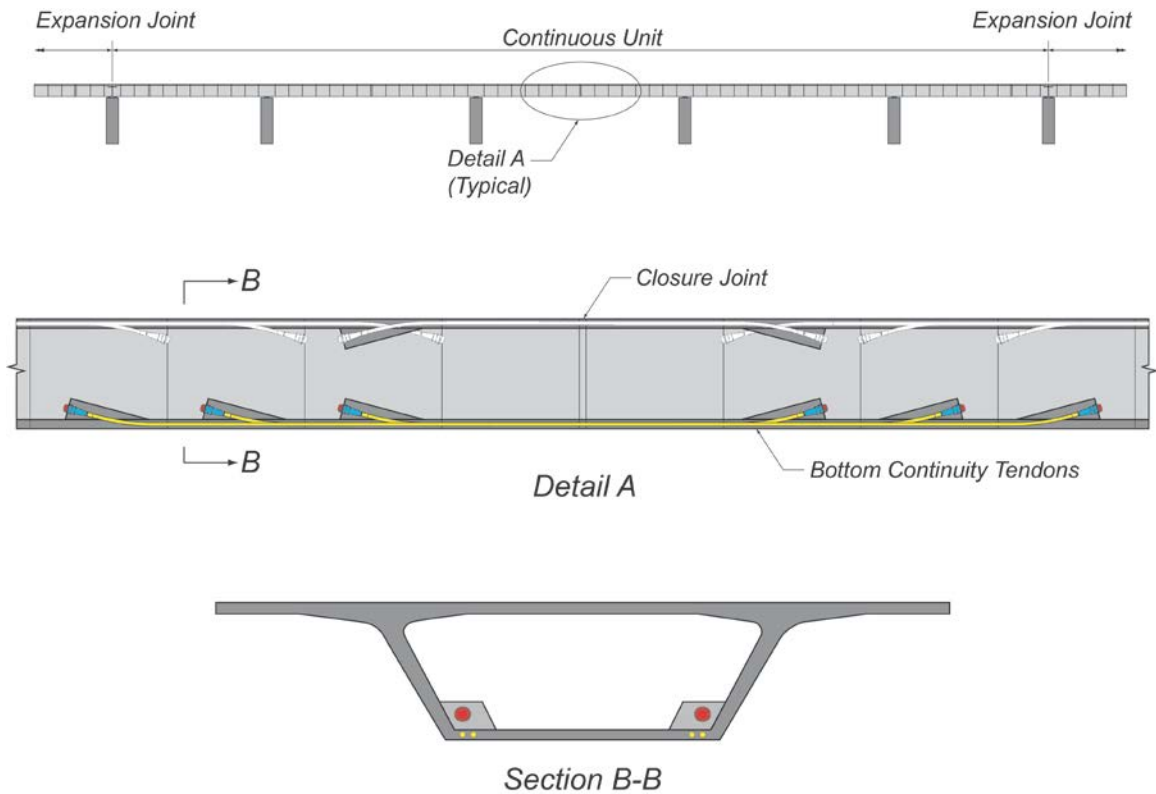


Figure 1.13 - Bottom Continuity Tendons for Balanced Cantilever Construction

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

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 1.14 shows details of typical top continuity tendons.

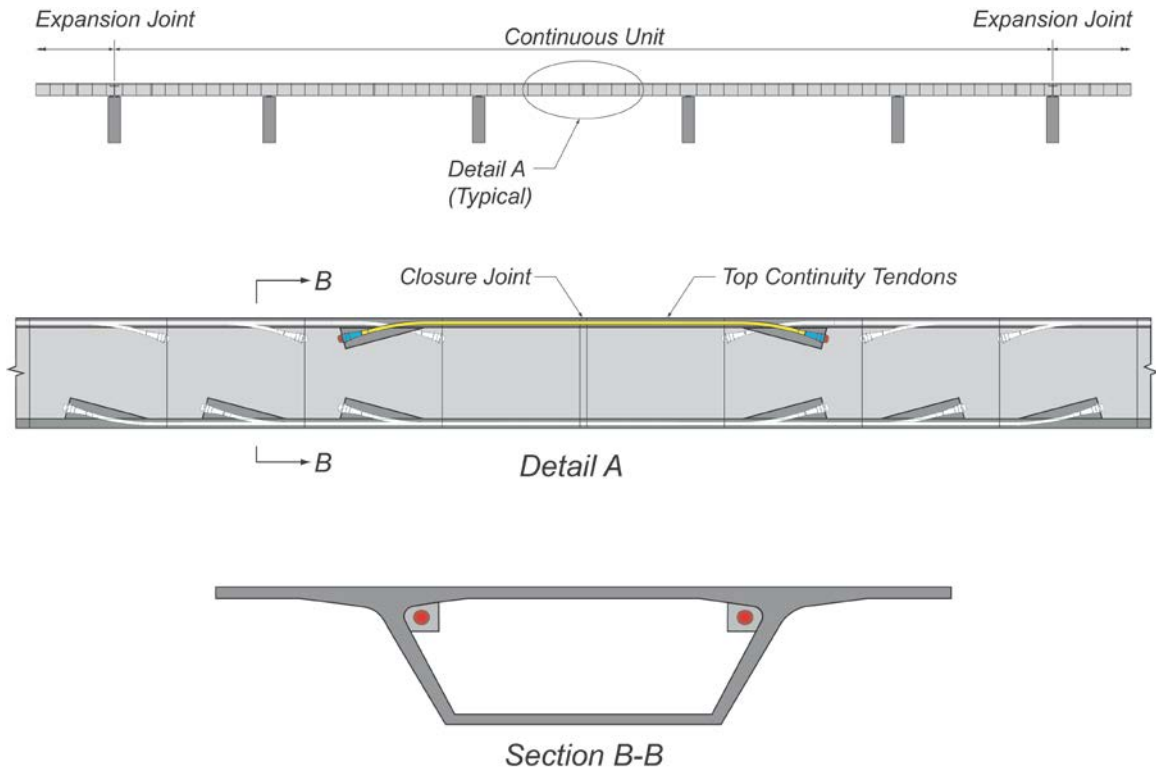


Figure 1.14 - Top Continuity Tendons for Balanced Cantilever Construction

1.2.3.4 Continuity Tendons in End Spans

Several segments constructed on falsework are typically needed to complete an end span of a balanced cantilever bridge at abutments or expansion spans between continuous units. A cast-in-place closure joint connects the cantilever to the segments on falsework and continuity post-tensioning tendons are installed, as shown in Figure 1.15. 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.

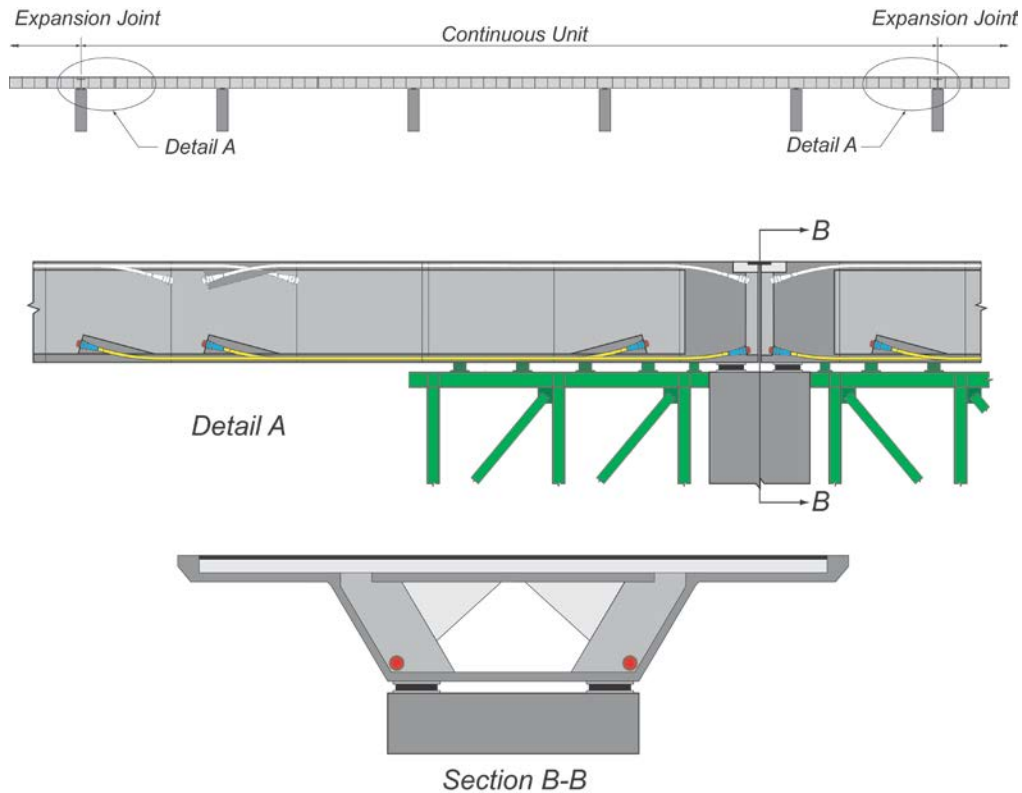


Figure 1.15 - Bottom Continuity Tendons near Expansion Joint at a Support

1.2.3.5 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 1.16). This location was chosen over hinges at 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.

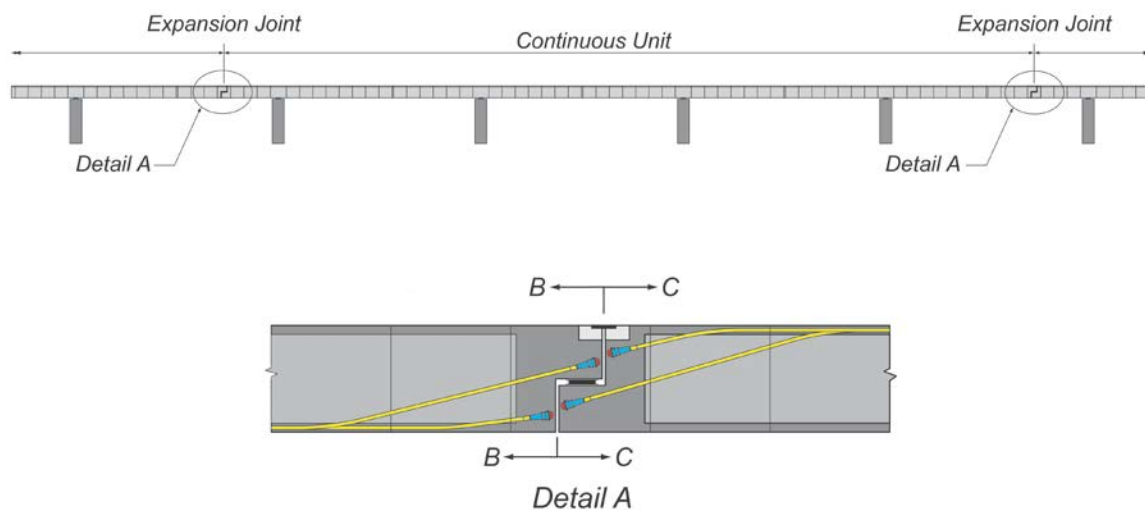


Figure 1.16 - In-Span Hinges in Balanced Cantilever Construction

1.2.4 Cast-in-Place Segmental Balanced Cantilever Bridges

An often used alternate to balanced cantilever construction using precast segments is cast-in-place balanced cantilever construction using form travelers. Form travelers support the concrete of the newly cast segment until it has reached a satisfactory strength for post-tensioning. The types of longitudinal post-tensioning tendons used in cast-in-place balanced cantilever construction are the same as for precast segment balanced cantilever.

Figure 1.17 shows the cast-in-place balanced cantilever construction of the Acosta Bridge in Jacksonville, Florida. Figure 1.18 shows typical construction phasing for a three span bridge built by the cast-in-place balanced cantilever method using form travelers.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual



Figure 1.17 - Cast-In-Place Segmental Construction using Form Travelers

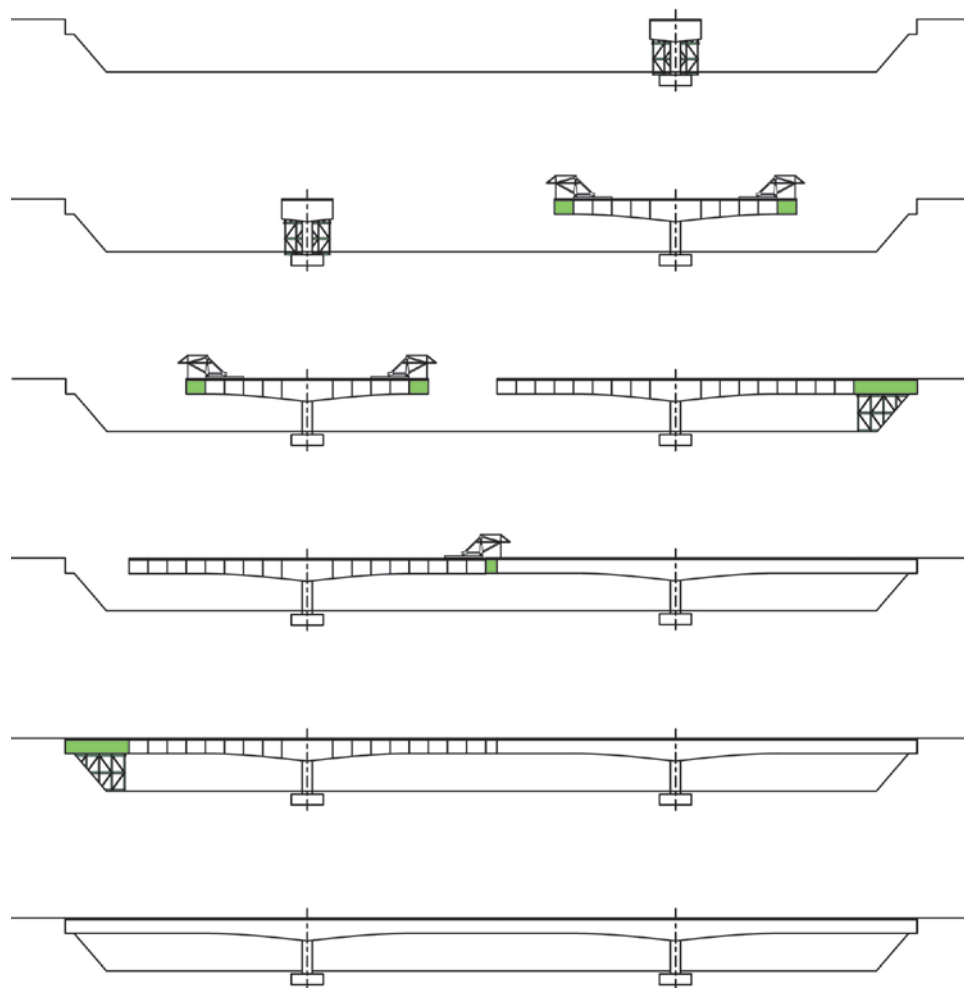


Figure 1.18 - Typical Construction Stages for Cast-In-Place Balanced Cantilever Construction

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 1.19 shows typical phases for span-by-span construction.

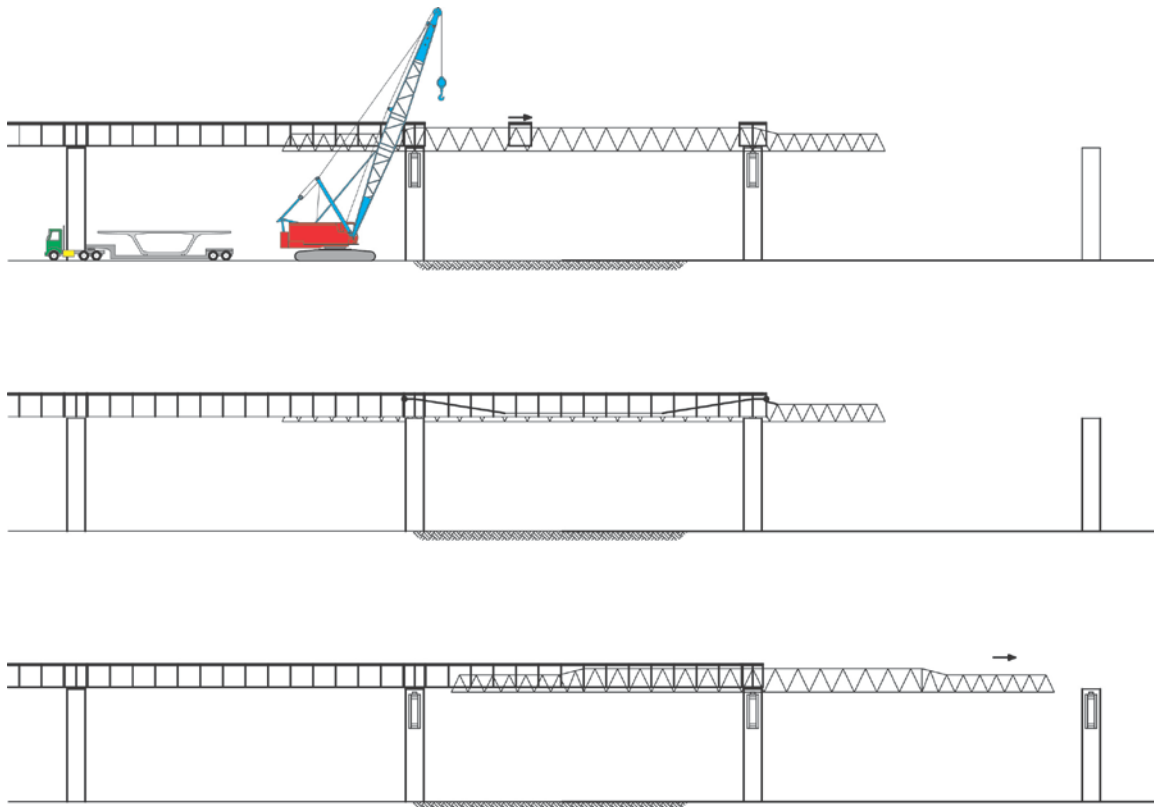


Figure 1.19 - Span-By-Span Construction

The erection schematic shown in Figure 1.19 shows temporary erection trusses used to support the precast segments during construction. Overhead erection gantries are also commonly used to support the segments during erection.

1.2.5.1 External Tendons

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 1.20 shows a typical layout of span-by-span tendons for an interior span where all tendons deviate at a common deviation saddle.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

The tendons from one span overlap with the tendons of the next in the top of the pier segment to achieve continuity between the spans. 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.

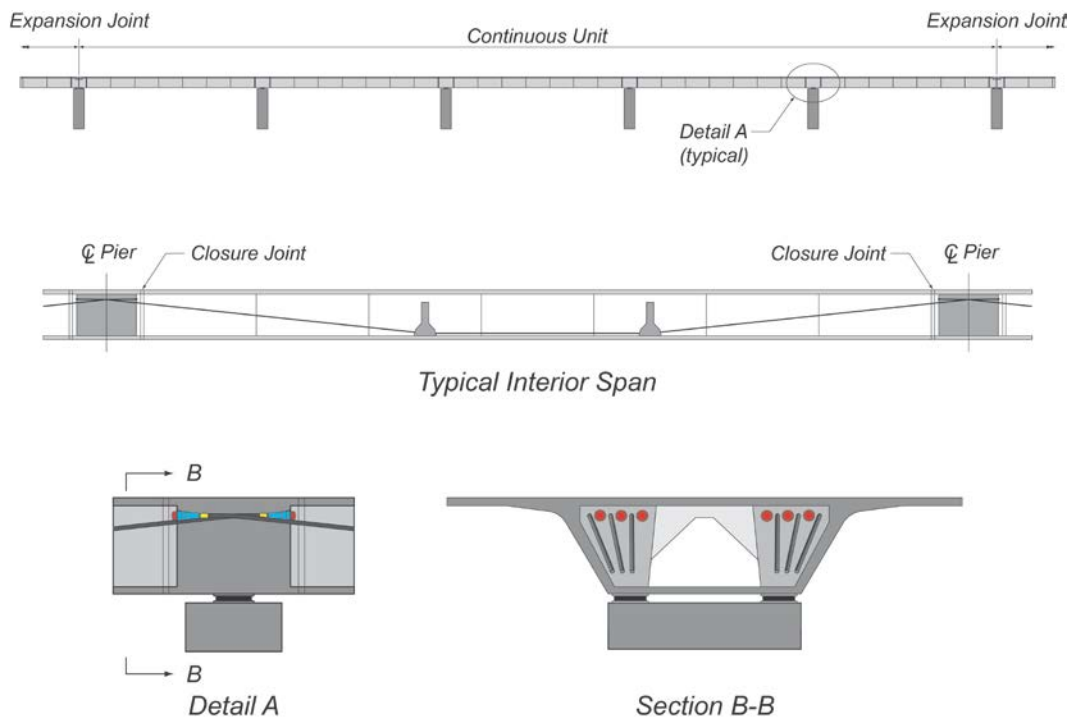


Figure 1.20 - Typical Span Post-Tension for Span-By-Span Construction

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Figure 1.21 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.

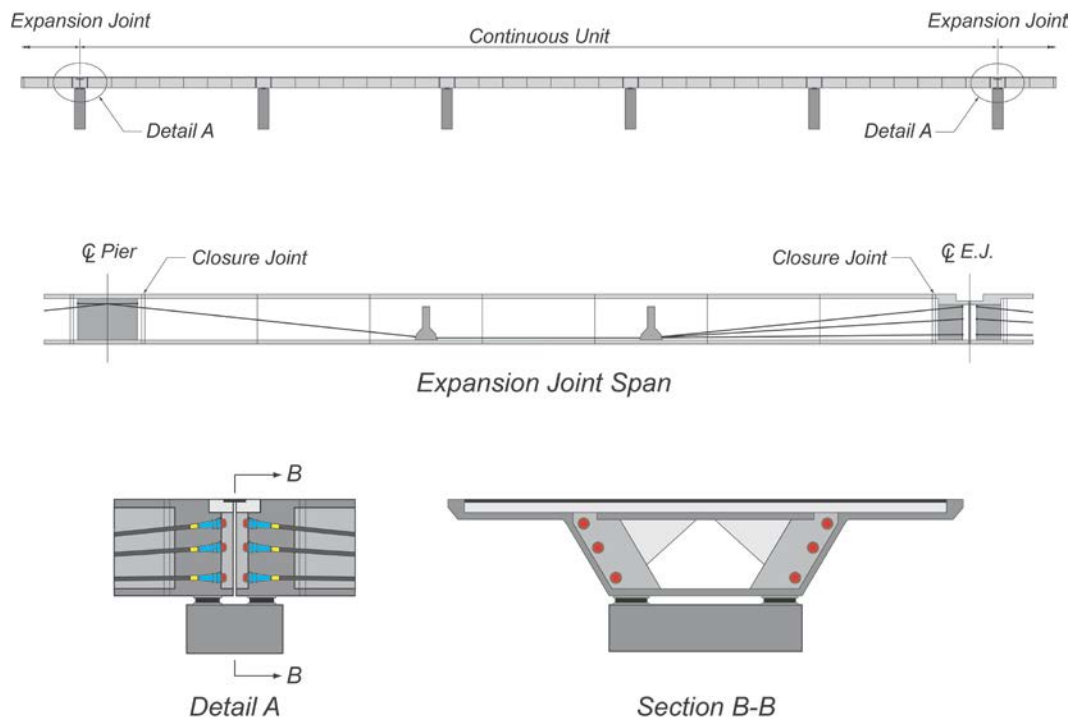


Figure 1.21 - Expansion Joint Span Post-Tensioning for Span-By-Span Construction

1.2.5.2 Tendons that are Partially External and Partially Internal

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 1.22). 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.

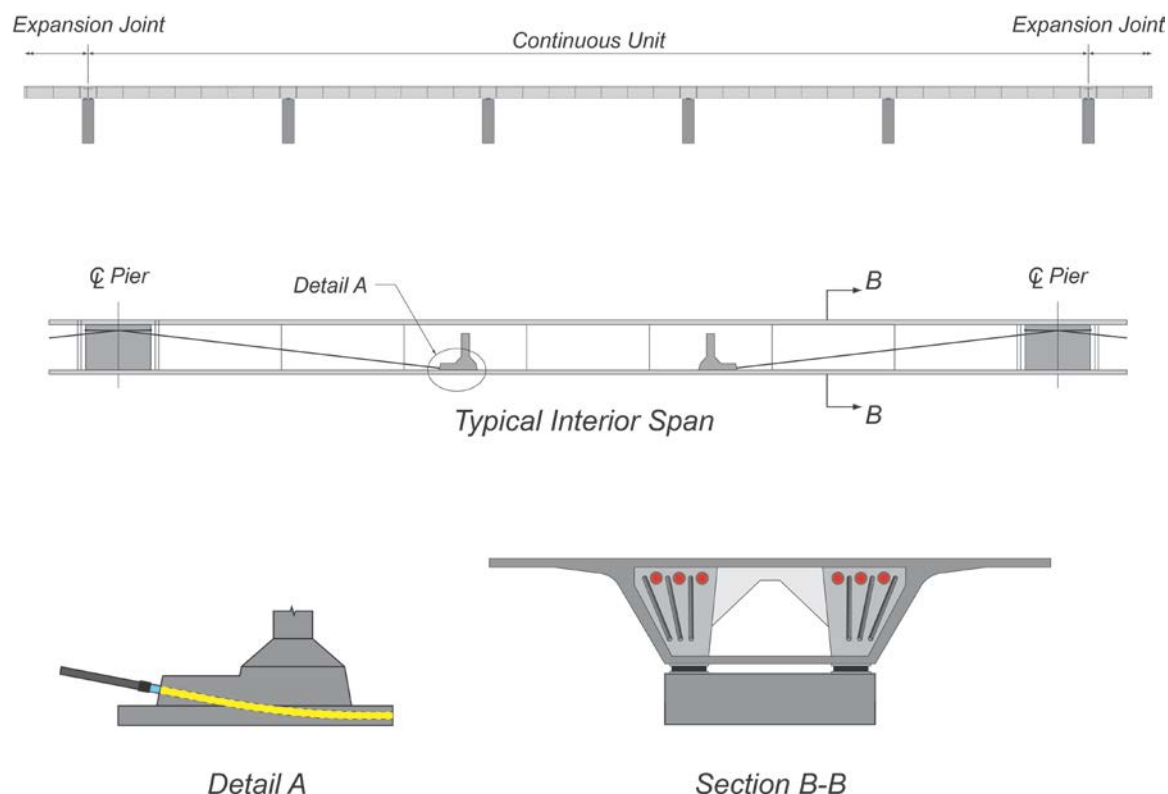


Figure 1.22 - External/Internal Span-By-Span Tendons

1.2.6 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 1.23). 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 1.23 - Progressive 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.

1.2.7 Transverse Post-Tensioning of Superstructures

Transverse post-tensioning is often used to precompress superstructure systems to offset unwanted transverse tensile stresses. The most fundamental use of these tendons is in cast-in-place concrete slabs. Spans comprised of precast planks or box beams are often joined by transverse tendons used in conjunction with longitudinal cast-in-place closure joints. Transverse post-tensioning is widely used in deck slabs of cast-in-place or precast segmental bridges.

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

1.2.7.1 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 2 to 3 feet along the length of 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 1.24 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.

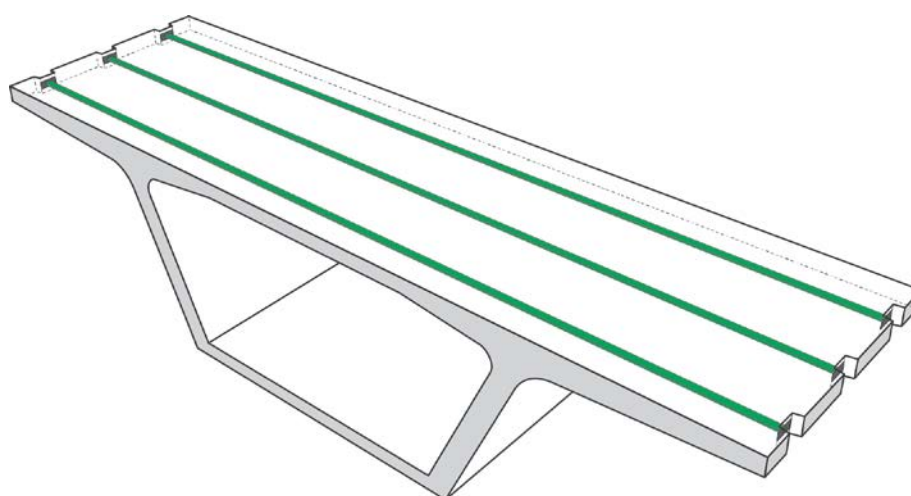


Figure 1.24 - Transverse Post-Tensioning in the Top Slab of Box Girder

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.

1.2.7.2 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.

1.2.7.3 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 1.25). 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 1.25, 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.

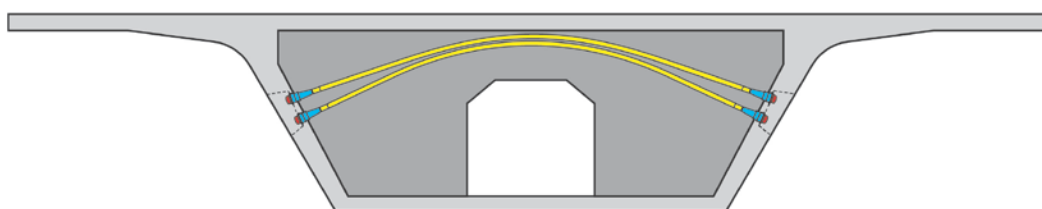


Figure 1.25 - Transverse Post-Tensioning in Diaphragms

1.2.7.4 Vertical Post-Tensioning in Diaphragms

Vertical post-tensioning bars (Figure 1.26) 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.

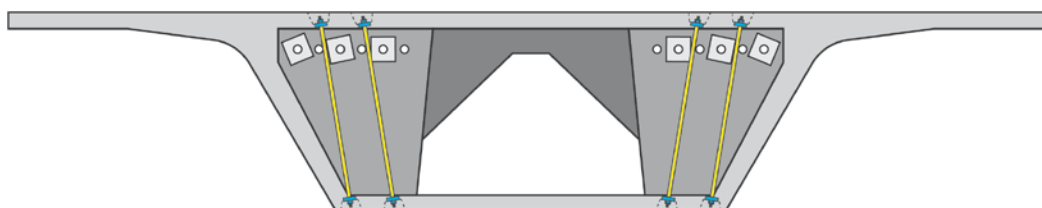


Figure 1.26 - Vertical Post-Tensioning in Diaphragms

1.2.7.5 Transverse Post-Tensioning in Deviator Ribs of Precast Segments

Transverse deviator ribs of span-by-span bridges may contain tendons (usually straight bars) in the top of the ribs across the bottom slab anchored in the web face (Figure 1.27). These are internal and are stressed and grouted in the casting yard.



Figure 1.27 - Transverse Post-Tensioning in Deviator Ribs

1.2.7.6 Vertical Post-Tensioning in Webs

Vertical post-tensioning bars are occasionally added to webs (Figure 1.28), 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.

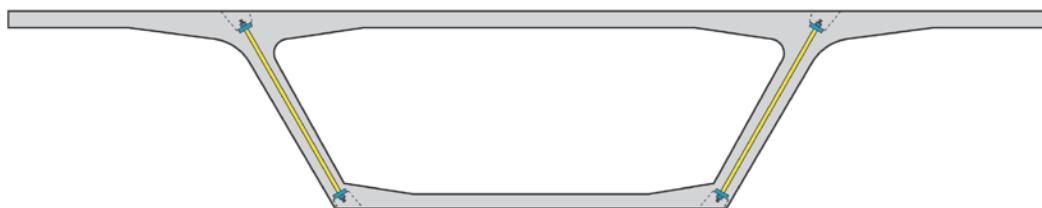


Figure 1.28 - Vertical Post-Tensioning in Webs

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.

1.2.8 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.

1.2.8.1 Hammerhead Piers

Transverse post-tensioned tendons using strand or bar tensile elements provide an effective reinforcing scheme for Hammerhead Piers (Figure 1.29). 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.

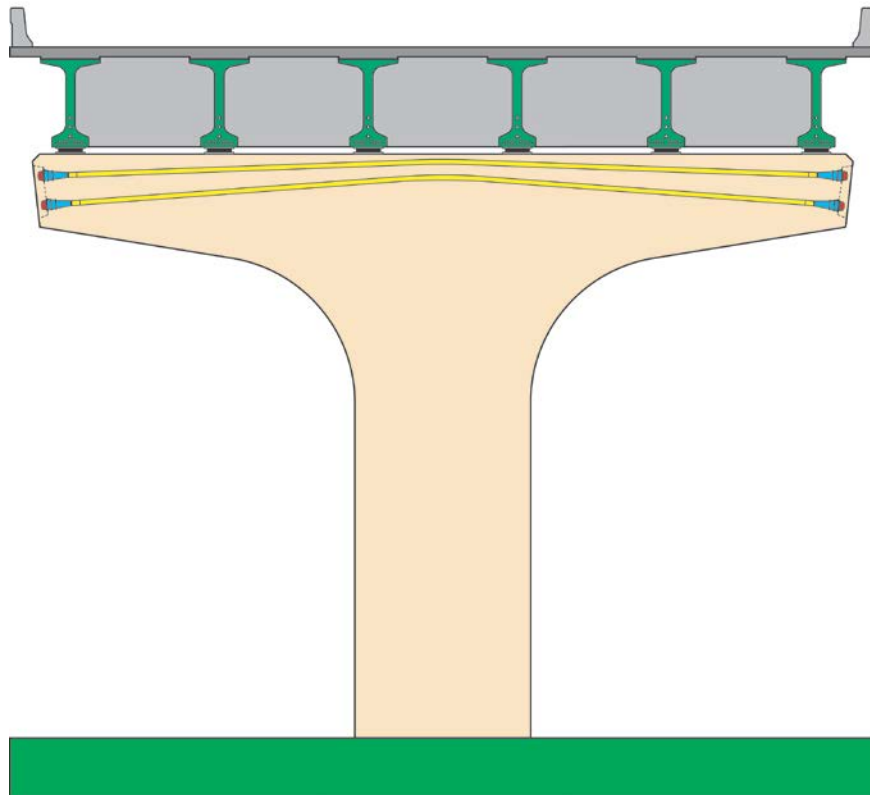


Figure 1.29 - Post-Tensioning in Hammerhead Piers

1.2.8.2 Straddle Bents

Straddle bents are often required to support upper level roadways in complex multi-level interchanges (Figure 1.30). 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.

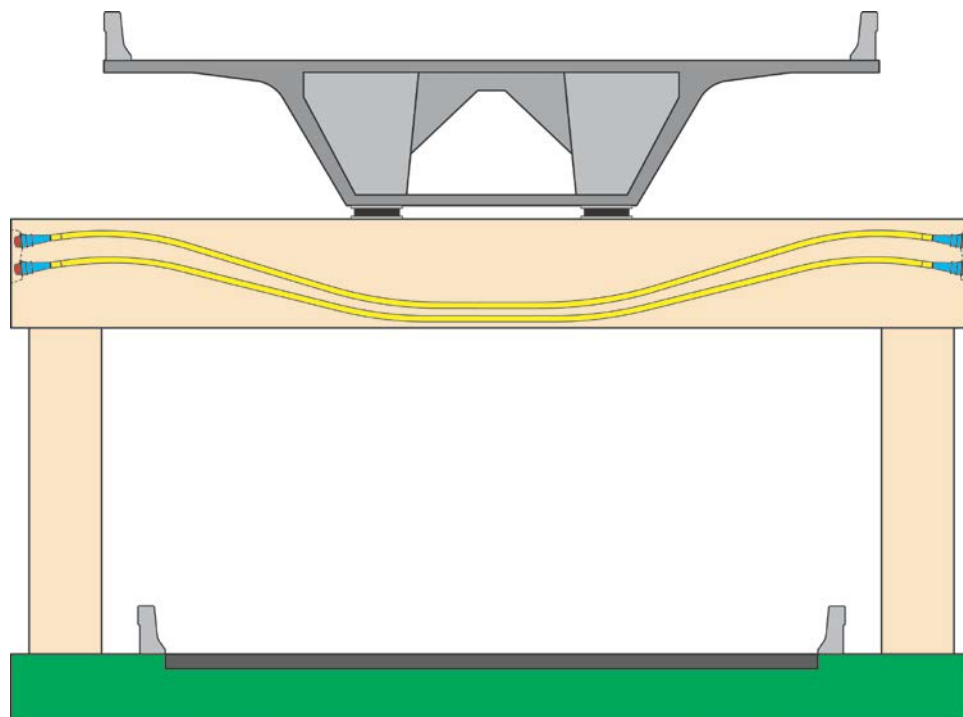


Figure 1.30 - Post-Tensioning in Straddle Bents

1.2.8.3 Cantilever Piers

Cantilever piers (C-piers) are also 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 1.31).

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.

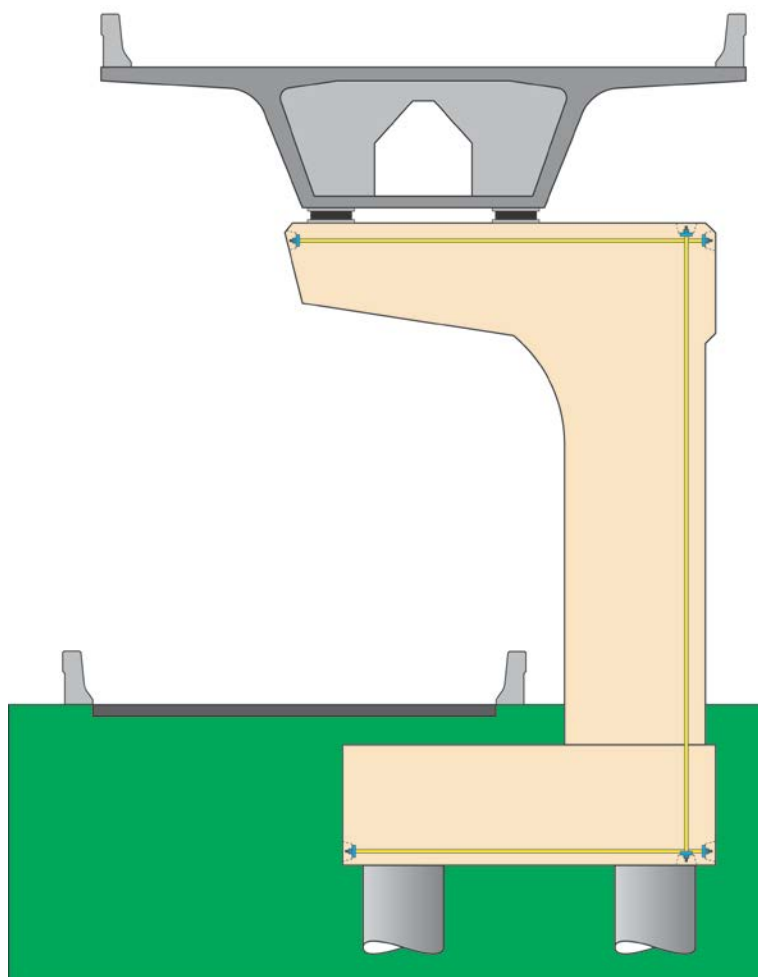


Figure 1.31 - Post-Tensioning in Cantilever Piers

1.2.8.4 Precast Piers

Precast concrete segmental piers with vertical post-tensioning have been used on several projects. Vertical post-tensioning usually consists of PT bars for short to moderate heights. Strand tendons are typically required 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 were used for the Foothills Bridge No. 2 on the Foothills Parkway in Tennessee (Figure 1.32).



Figure 1.32 - Precast Hollow Segmental Piers, Foothills Bridge No. 2

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

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 1.33).

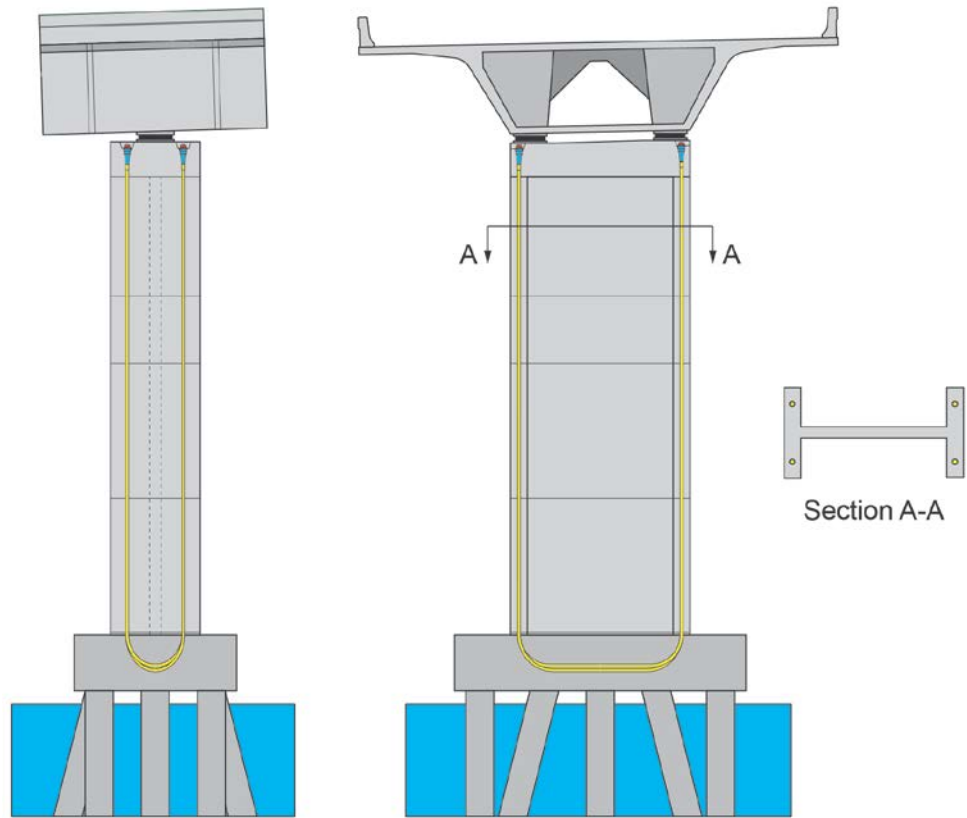


Figure 1.33 - Precast I-Piers

1.2.8.5 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 1.34). 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. Strand tendons were used to make continuity of the two arch halves, and to prestress against flexure in the crown-loaded arch.



Figure 1.34 - Natchez Trace Parkway Arches, Tennessee

1.2.8.6 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 segmental balanced cantilever construction. 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 longitudinal 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.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Depending on the size of the segment, there may be three 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 external 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. Figure 1.35 shows the application of epoxy on the Foothills Bridge No. 2. Figure 1.36 shows the stressing of temporary post-tensioning bars for the same project.



*Figure 1.35 - Applying Epoxy between Precast Segments
at the Foothills Parkway Bridge No. 2*



*Figure 1.36 - Stressing Temporary Bar in Bottom Slab
of the Foothills Parkway Bridge No. 2*

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.

This Page Intentionally Left Blank.

Chapter 2 – Post-Tensioning System Materials and Components

Satisfactory performance of post-tensioned bridges depends upon the appropriate selection, design, specification and fabrication of various materials and components that make up the post-tensioning system. This chapter offers general guidance and information for materials and components. Some of the information in this chapter is taken from various industry specifications and information from manufacturers and suppliers. Two important resources are “Specifications for Grouting of Post-Tensioned Structures” (PTI M55.1-12) and “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12).

2.1 Prestressing Steel

2.1.1 Strands and Bars

2.1.1.1 Strands

Strand for post-tensioning is made of high tensile strength steel wire. A strand is comprised of 7 individual wires, with six wires helically wound to a long pitch around a center “king” wire. All strand should be Grade 1860 MPa (270 ksi) low relaxation, seven-wire strand conforming to the requirements of ASTM A416 “Standard Specification for Steel Strand, Uncoated Seven Wire Strand for Prestressed Concrete.” ASTM A416 provides minimum requirements for mechanical properties (yield, breaking strength, elongation) and maximum allowable dimensional tolerances. Strand from different sources may meet ASTM A416 but not necessarily be identical in all respects.

Strand is most commonly available in two nominal sizes, 12.7mm (0.5in) and 15.2mm (0.6in) diameter, with nominal cross sectional areas of 99mm² and 140mm² (0.153 and 0.217 square inches), respectively. Though the majority of post-tensioning hardware and stressing equipment is based on these sizes, the use of 15.7mm (0.62in) diameter strand has been increasing.

Strand size tolerances may result in strands being manufactured consistently smaller than, or larger than nominal values. Recognizing this, “Acceptance Standards for Post-Tensioning Systems” (Post-Tensioning Institute, 1998) refers to the “Minimum Ultimate Tensile Strength” (MUTS), which is the minimum specified breaking force for a strand. Strand size tolerance may also affect strand-wedge action leading to possible wedge slip if the wedges and strands are at opposite ends of the size tolerance range.

Strand conforming to ASTM A416 is relatively resistant to stress corrosion and hydrogen embrittlement due to the cold drawing process. However, since susceptibility to corrosion increases with increasing tensile strength, caution is necessary if strand is exposed to corrosive conditions such as marine environments and solutions containing chloride or sulfate, phosphate, nitrate ions or similar. Consequently, ASTM A416 requires proper protection of strand throughout manufacture, shipping and handling. Protection during the project, before and after installation, should be specified in project drawings and specifications.

Various methods have been developed to provide improved corrosion protection to individual prestressing strands. Some of these methods include:

- Greased and plastic sheathed mono-strand for unbonded tendons has been widely used in buildings, but not generally in bridges in the United States. Plastic sheathed mono-strands are, however, available for cable-stays or external tendon applications for new structures and the repair of old ones.
- Epoxy coated strand meeting the same requirements as ASTM A416 is available and should also conform to ASTM A882 “Standard Specification for Epoxy-Coated Seven Wire Strand.” Epoxy coated strand is available as an outer coating only, or as a coating that also fully fills the interstices between wires. The latter is preferred for post-tensioning or cable stay applications. Special wedges are required that bite through the thickness of the coating and engage the strand; power seating of the wedges is usually required.
- Strand made from fiber material (such as carbon or aramid fibers) has limited application as post-tensioning to date. These composite materials offer advantages for enhanced corrosion resistance, but lack the benefit of a high modulus of elasticity that is routinely provided by steel and which is crucial to good load-deflection behavior of a prestressed structure without excessive cracking under service loads.
- Few U.S. manufacturers supply galvanized strand. The galvanizing process leads to some reduction in tensile strength of prestressing steel. This reduction is typically compensated by starting the wire drawing process with rod of higher strength (or utilizing larger rod for drawing) so that at conclusion of the process dimensions and minimum strength specified for equivalent non-galvanized prestressing wire is achieved. This strand is not typically used in U.S. bridges.

Tendons in prestressed concrete structures do not experience stress cycling significant enough to induce fatigue problems. Fatigue is a concern only in certain applications such as cable-stays in cable-stayed bridges where traffic loads significantly affect stress variations.

2.1.1.2 Bars

Bars should be Grade 1035 MPa (150 ksi), high strength, thread bar meeting the requirements of ASTM A722, “Standard Specification for Uncoated High-Strength Steel Bar for Prestressing Concrete,” Type II bar. Bars are available in both a coarse and fine thread depending on the manufacturer. Each may have advantages in different situations. It is good practice to limit the stress level and number of re-uses for temporary applications, according to recommendations of the Manufacturer. In the absence of such information, it is suggested that for new bars, the stress should not exceed 50% f_{pu} and the number of re-uses be conservatively selected based on the critical nature of usage. Re-use of bars should only be after inspection for damage from previous uses.

Post-tensioning bars are available in various sizes from 16mm (5/8in) to over 50mm (2in) diameter. However, for convenience in handling, installation, and removal and re-use in normal applications for post-tensioned bridges, 32mm (1-1/4in) or 35mm (1-3/8in) diameter bars are typically used.

Bars are not as easily damaged by corrosion as strands because of their lower strength, large diameter and smaller ratio of exposed surface to cross section area. Hot rolled bars also acquire a natural surface oxidation from the rolling process that enhances their protection. Nevertheless, bars need to be protected during extended periods of exposure especially in aggressive environments.

2.1.2 Shipping, Handling and Storage

All prestressing steel should be protected against physical damage and corrosion at all times from manufacture to final installation and grouting. It should be packed in containers for shipping handling and storage. A rust-preventing corrosion inhibitor should be placed in the package or be incorporated in the carrier type packaging material. The corrosion inhibitor should have no deleterious effect on the steel or grout or on the bond strength of steel to grout. The inhibitor carrier type packaging should conform to Federal Specification MIL-P-3420. Damaged packaging should be replaced or restored to its original condition.

All bars of each size from each mill heat of steel and all strand from each manufactured reel to be shipped to the site should be assigned an individual LOT number and be tagged in a manner that each such LOT can be accurately identified at the site. All unidentified prestressing steel (strand or bar) or loss of positive proof of identification is sufficient reason for rejection.

Shipping containers should be clearly marked with a statement that it contains high-strength prestressing steel, the type of care needed for handling, the type and amount of corrosion inhibitor used and the date it was placed, and any other safety precautions and instructions. Strand should be clearly identified that it is low-relaxation (stabilized) strand per the requirements of ASTM A416 and the corresponding LOT number for which quality control test samples have been taken. Strands not so designated should be rejected.

Reels of strand should be examined by the Contractor and inspected by the Construction Inspector when first received on site and periodically while in storage. During use, any reel that is found to contain broken wires or corrosion should be carefully examined. Lengths of strand containing broken wires or corrosion should be removed and discarded. Prestressing steel should also be protected during installation in the structure.

Post-tensioning bars for both temporary and permanent applications should be identified in a similar manner and inspected for damage or excessive corrosion. At any time during construction, the Construction Inspector should have the authority to reject any prestressing steel that has sustained physical or corrosion damage.

2.1.3 Acceptance

To ensure that correct materials are supplied and used, specific quality control procedures for material acceptance should be in place. Procedures may differ from State to State or from Owner to Owner. An Owner may require that post-tensioning systems be pre-qualified prior to use in construction by the Owner's pre-qualification program. Pre-qualification in this manner involves prior submission and approval of test reports and certifications.

Samples for testing should be furnished at the job site for each manufacturer of prestressing steel and bar. Each sample furnished for testing should be accompanied by certification showing:

- Coil/reel number (strand only);
- Heat number;
- Chemical composition;
- Yield strength;
- Breaking strength; and
- Elongation properties

An example of typical frequencies of sampling and LOT designations are, as follows:

- For strand: three randomly selected samples, 1.5m (5ft) long, per manufacturer, per size of strand, per shipment, with a minimum of one sample per ten delivered reels and minimum of one per LOT/HEAT.
- For bar: three randomly selected samples, 1.5m (5ft) long, per size of bar, per heat of steel with a minimum of one sample per shipment.

One of each of the samples furnished to represent a LOT should be tested in accordance with appropriate ASTM standard. The remaining samples should be properly identified, tagged, and stored. In the event of a loss or failure, the stored samples should be used for evaluation. For acceptance of the LOT represented, test results must demonstrate 100% of f_{pu} .

Following initial acceptance, the Contractor should maintain good control over the storage, identification, and record keeping regarding the prestressing steel. The Contractor should supply copies of certifications and test results to the Construction Inspector. The latter should regularly and periodically check stored components, records and results.

Prior to use, strand should be inspected with respect to corrosion. Refer to Section 11.5 of "Guide Specification for Grouted Post-Tensioning" (PTI/ASBI M50.3-12) for strand condition/acceptance with regard to corrosion.

Approval of any prestressing materials by the Construction Inspector should not preclude subsequent rejection if material is damaged in transit or later found to be defective for any reason. Costs of acceptance and quality control tests are typically included in the project bid items for post-tensioning work and no separate payment is made. Testing should conform to the applicable ASTM Specifications. The location where the post-tensioning is to be installed is considered the "site" and may be the project site or a casting yard.

2.2 Anchorages and Associated Hardware

2.2.1 Anchorages

2.2.1.1 Basic Bearing Plates

A basic bearing plate is a flat plate bearing directly against concrete. This includes square, rectangular, or round plates, sheared or torch cut from readily available steel plate, normally ASTM A36. Basic bearing plates are used in conjunction with galvanized sheet metal or plastic trumpets to transition from the strand spacing in the wedge plate to the duct (Figure 2.1).

Basic bearing plate anchorages should comply with the requirements of Section 10.3.2 of the AASHTO LRFD Bridge Construction Specifications.

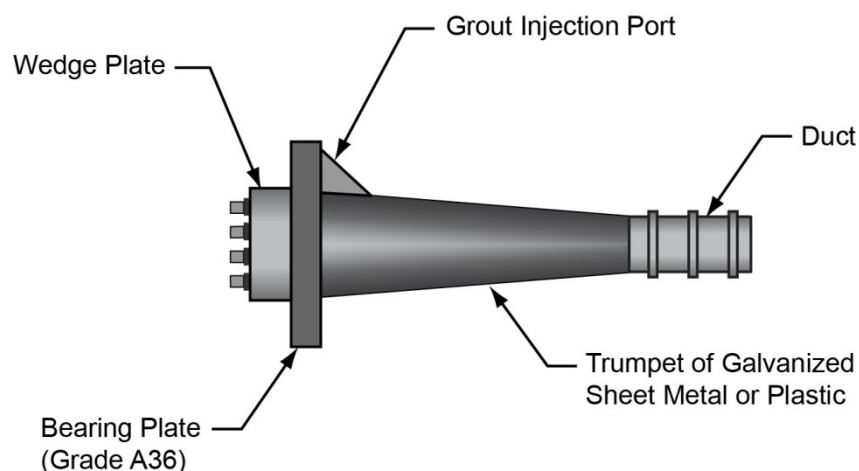


Figure 2.1 - Basic Bearing Plate Anchorage System

2.2.1.2 Special Bearing Plates or Anchorage Devices

A special bearing plate or anchorage device is any anchorage hardware that transfers tendon force into the concrete but does not meet normal analytical design requirements for basic bearing plates. Covered by this definition are devices having single or multiple plane bearing surfaces, and devices combining bearing and wedge plate in once piece. These anchorages typically require increased confinement reinforcement and should be accepted on the basis of physical tests. Figure 2.2 shows a cut-away view of a multi-plane anchorage system. Figure 2.3 shows the components of the anchorage system for a four strand tendon in flat duct, commonly used in slabs.

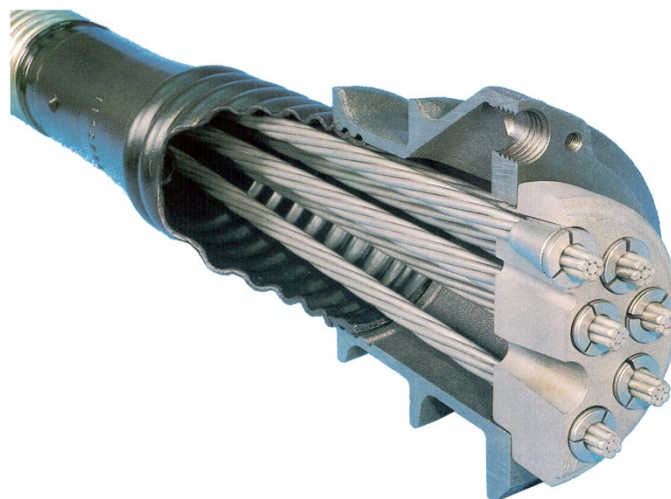


Figure 2.2 - Multi-Plane Anchorage System (Courtesy of VSL)



Figure 2.3 - Anchorage System for Flat Duct Tendon (Courtesy of DSI)

Use of a special bearing plate or anchorage device is acceptable if it complies with the testing requirements of Section 10.3.2.3 of the AASHTO LRFD Bridge Construction Specifications.

2.2.1.3 Wedge Plates

Wedge plates, in conjunction with wedges, transfer the prestressing force in the strands to the anchorage. Wedge plates should comply with PTI's "Guide Specifications for Grouted Post-Tensioning," Section 4.3.2.

2.2.1.4 Wedges and Strand-Wedge Connection

Wedge performance is critical to the proper anchoring of strands. Different wedges have been developed for particular systems and applications such that there is no single standard wedge. However, wedges for post-tensioning systems should have the following characteristics:

- Wedge length at least 2.5 times the strand diameter.
- Wedge angle of 5 to 7 degrees.
- Internal serrated teeth for gripping the strand.
- Case-hardened low carbon or alloy steel.
- Two or three parts with a spring wire retainer clip or o-ring in a groove around the thick end.

Wedges are case hardened with a ductile core, in order to bite into the strand and conform to the irregularity between the strand and wedge hole. In so doing, the surface may crack. This is normally acceptable and does not affect performance so long as wedge sections do not break completely into separate pieces. Often, it is only the portion outside the retainer ring that cracks.

Wedges should comply with PTI's "Guide Specifications for Grouted Post-Tensioning," Section 4.3.2.

2.2.2 Post-Tensioning Bars Anchor Systems

Anchorage systems for post-tensioning bars are comprised of bearing plates and anchor nuts similar to the components shown in Figure 2.4. The anchorage system should comply with PTI's "Guide Specifications for Grouted Post-Tensioning," Section 4.3.2.



Figure 2.4 - Post-Tensioning Bar Anchorage System (Courtesy of DSI)

2.2.3 Permanent Grout Caps

Permanent grout caps similar to those shown in Figure 2.5 should be provided in accordance with Protection Levels specified in Section 3.0 of “Guide Specification for Grouted Post-Tensioning PTI/ASBI,” M50.3-12. Project specific documents should specify when and where caps are required.

Permanent grout caps should be made of a non-corrosive material such as fiber reinforced plastic, stainless steel, or galvanized ferrous metal with a minimum thickness of zinc of 120 μm . To ensure an enduring, maintenance-free, life of 75 years fiber reinforced plastic caps should contain an anti-oxidant additive with an environmental stress cracking endurance of 192 hours per ASTM D1693; stainless steel caps should meet the requirements of ASTM A240 Type 316.

Grout caps shall meet the requirements of PTI/ASBI M50.3-12 Section 4.3.3.



Figure 2.5 - Permanent Plastic Grout Caps (Courtesy of VSL)

2.3 Ducts

Ducts are used to form a continuous void through the concrete for later placement of the post-tensioning tendon steel. Originally, little attention was paid to the possible role of the duct as a barrier to corrosive agents. Today, strong emphasis is placed on the quality, integrity and continuity of the duct as a corrosion barrier in itself. This has resulted in a move toward the use of plastic ducts in some states. Nevertheless, previous duct materials are still available and their use continues in other regions. Consequently, the following recommendations should be adapted as appropriate to meet local needs and conditions in accordance with Protection Levels specified in Section 3.0 of “Guide Specification for Grouted Post-Tensioning PTI/ASBI,” M50.3-12.

2.3.1 Duct Size

2.3.1.1 Strand Tendons

Section 5.4.6.2 of the AASHTO LRFD Bridge Design Specifications calls for the inside cross-sectional area of the duct to be at least 2.0 times the net area of the strand tendon. The one exception cited by AASHTO is in the case where the tendons are to be placed by the pull-through method. In this case, the inside duct area should be 2.5 times the net area of the strand tendon. Section 4.3.5 of “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12) standardizes the inside cross-sectional area of the duct to be at least 2.5 times the net area of the strand tendon cross sectional area.

Oval “flat” ducts are commonly used for transverse tendons in deck slabs of concrete box girders. These transverse tendons have typically been made of up to 4 strands of 0.6in diameter, though there are systems that will accept up to 5 strands. The internal clear dimensions of oval duct should be a minimum of 25mm (1 in) vertically and 75mm (3 in) horizontally.

2.3.1.2 Bar Tendons

Tendons containing a single post-tensioning bar should have an internal duct diameter at least 12mm (½ in) greater than the maximum outside dimension of the bar or bar coupler. A greater clearance may be preferred or be necessary for some applications. Examples of this use would be to provide greater tolerance for temporary bars or to accommodate bridges with slightly curved alignments.

2.3.2 Ducts for Tendons

2.3.2.1 Corrugated Steel

Corrugated steel ducts are spirally wound to the necessary diameter from strip steel with a minimum wall thickness of 0.45mm (26-gauge) for ducts less than 66mm (2-5/8 in) diameter or 0.6mm (24-gauge) for ducts of greater diameter. The strip steel should be galvanized to ASTM A653/A653M with a coating weight of G90. Corrugated steel ducts should be manufactured with welded or interlocking seams with sufficient rigidity to maintain the correct profile between supports during concrete placement (Figure 2.6). Corrugated steel ducts should also be able to flex without crimping or flattening. Joints between sections of duct and between ducts and anchor components should be made with positive, metallic connections that provide a smooth interior alignment with no lips or abrupt angle changes.

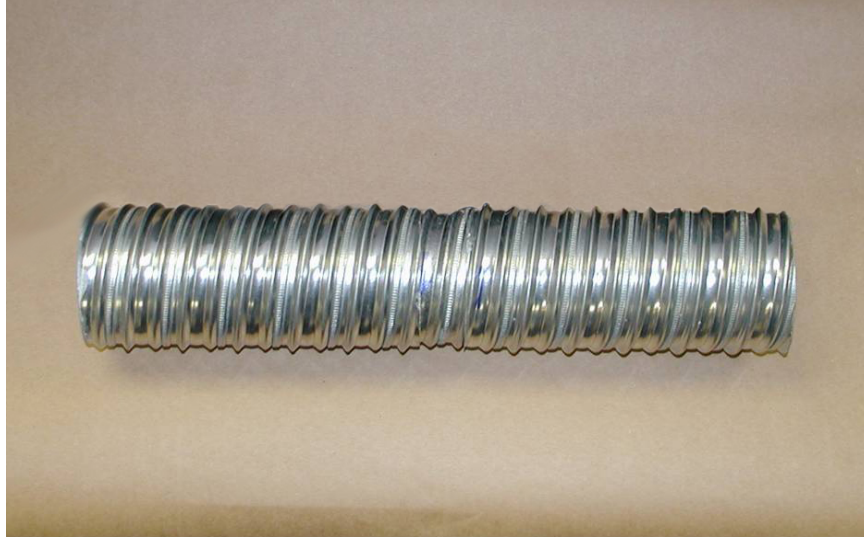


Figure 2.6 - Corrugated Metal Duct

2.3.2.2 Smooth, Rigid, Steel Pipe

Rigid steel ducts are typically used in those portions of external tendons deviating through segmental bridge pier segment diaphragms or deviators. In these areas of curved tendon alignments, the steel pipe should be pre-fabricated to the required radius. Smooth steel pipes should conform to ASTM A53/A53M "Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc Coated, Welded and Seamless," Grade B Schedule 40.

2.3.2.3 Corrugated Plastic

Corrugated plastic ducts, as shown in Figure 2.7, are also used for tendons internal to the concrete. These ducts should be seamless and fabricated from polyethylene or polypropylene meeting the requirements of Section 4.3.5.2 of "Guide Specification for Grouted Post-Tensioning" (PTI/ASBI M50.3-12).



Figure 2.7 - Corrugated Plastic Duct

2.3.2.4 Corrugated Plastic, Tight-Radius Duct

Corrugated plastic duct, specifically formulated for tight-radii applications, is an option to curved steel rigid ducts presented in Section 2.3.2.2. Locations for application of this type of duct include anchorage blisters, external tendon deviation points, and looped vertical tendons in precast, post-tensioned piers. When used in internal applications, the duct can be connected with the same duct splices as straight portions of corrugated plastic duct to provide a continuous duct from anchorage to anchorage. The duct can be pre-bent and delivered to the site similar to rigid steel duct.

The wear resistance of the tight-radius corrugated plastic duct should be confirmed for the minimum bend radius as a function of tendon size (number of strands). For further information, refer to “Improved Performance Using Corrugated Plastic Duct in Tight-Radius Post-Tensioning Applications” (Krauser).

2.3.2.5 Smooth, High Density Polyethylene Pipe (HDPE) for External Tendons

HDPE smooth pipe is available in different diameters, wall thickness, physical and chemical properties. Though there can be some variability in commonly available materials, all HDPE for ducts should conform to Section 4.3.5.3 of “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12). In addition, it is very important that the duct has satisfactory properties for handling, storage, installation and durability for the application.

The color of HDPE smooth pipe for duct is normally black from a small amount of carbon in the material, to protect against degradation from ultraviolet light. The wall thickness, diameter and physical strength (Hydrostatic Design Basis) should be sufficient to initially withstand grouting pressures, and in the long term, not deteriorate or split. Wall thickness requirements are specified in Section 10.8.3 of the AASHTO LRFD Bridge Construction Specifications.

2.3.2.6 Plastic Fittings and Connections for Internal Tendons

All duct splices, joints and connections to anchorages should be made with couplings and connectors that produce a smooth interior duct alignment with no lips or kinks. All fittings and connections between lengths of plastic duct and between ducts and steel components (e.g. anchors or steel pipe) should be made of materials compatible with corrugated plastic ducts. Plastic materials should contain antioxidant stabilizers and have an environmental stress cracking of not less than 192 hours as determined by ASTM D1693 "Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics," Condition C. Duct tape should not be used to join or repair ducts or make connections.

2.3.2.7 Grout Inlets, Outlets, Valves and Plugs

Grout inlets, outlets, valves and plugs should be made of polypropylene or polyethylene meeting the requirements for plastic, corrugated ducts. Grout inlets, outlets, valves and plugs shall meet the requirements of PTI/ASBI M50.3-12 Sections 4.3.12 and 4.4.4. Figure 2.8 shows grout vents installed in cantilever ducts of a precast segmental bridge pier segment.

Tubes for inlets and outlets for strand tendons should have a minimum inside diameter of 20mm (3/4 in). For bar tendons and for tendons comprising up to 4 strands, tubes should be at least 10mm (3/8 in) internal diameter. Inlets and outlets should be closeable with suitable valves or plugs. For grouting of long vertical tendons, dual mechanical shut-off valves are usually necessary to facilitate intermediate stages of grouting and venting.

Inlets and outlets should be arranged and attached to ducts, anchorages and grout caps in a manner that allows all air and water to escape in order to ensure that the system is completely filled with grout. (See Chapter 4 for examples of locations of inlets and outlets).

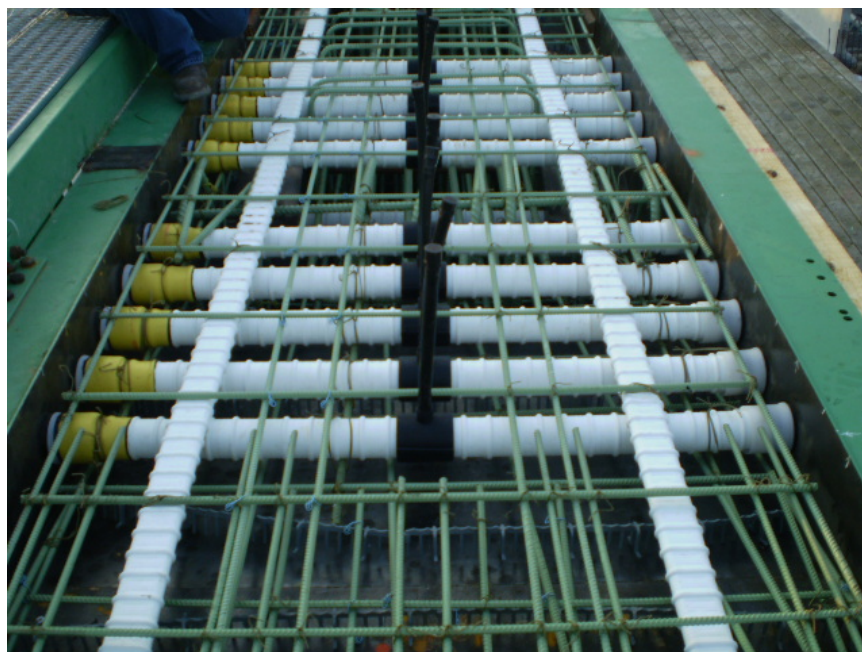


Figure 2.8 - Grout Vents at Center of a Precast Segmental Pier Segment

2.3.2.8 Duct Couplers for Precast Segmental Bridges

Duct couplers should be used at match-cast joints between precast segments and similar situations if necessary to create a continuous, air and water-tight seal. The duct couplers shall be mounted to the bulkhead of the casting machine to assure alignment between match cast segments, while having flexibility to accept some misalignment and angular deviation. During segment erection, the sealing gaskets and other details of the coupler should not prevent the match-cast joint from closing under the application of temporary post-tensioning. Figure 2.9 shows components of a typical duct coupler. Figure 2.10 shows duct couplers connected to the ducts and mounted to the bulkhead prior to casting a precast segment.



Figure 2.9 - Duct Coupler for Precast Segmental Internal Tendons

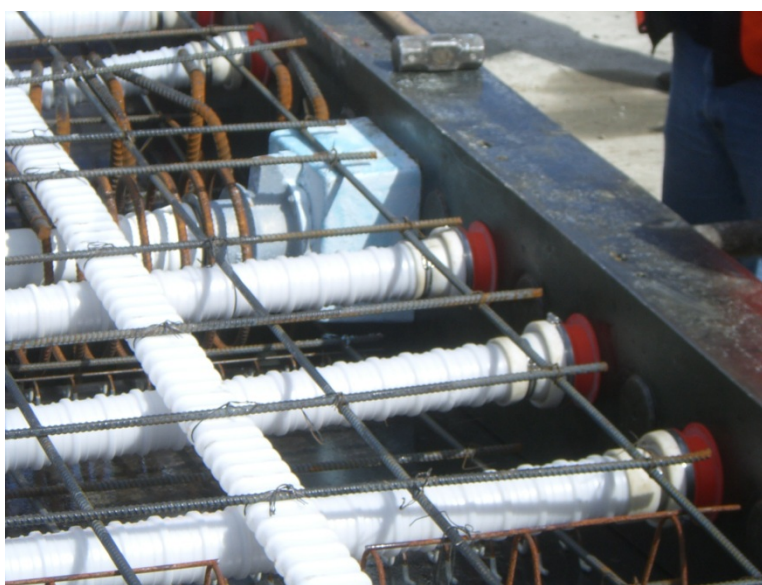


Figure 2.10 - Duct Couplers in Precast Segmental Construction

2.3.2.9 External Tendon Duct Connections

Connections between sections of plastic pipe should be made using heat welding techniques or with mechanical couplers. Connections between external HDPE pipe and steel pipe embedded in the concrete should be made using circular sleeve (boot) made of Ethylene Propylene Diene Monomer (EPDM). The sleeves should be secured with 10mm (3/8 in) wide power seated, 316 stainless steel band clamps, using one on each end of the sleeve (boot) to seal against leaking grout. Welded and Boot connections should be in accordance with Sections 4.3.9 and 4.3.11 of “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12).

2.3.2.10 Shrink Sleeves

Tendon connections may be enhanced by the use of shrink sleeve wrap overlaying the connection and portions of adjacent ducts. This may be used in aggressive environments where connections may be directly exposed to de-icing salts or other contaminants entering through expansion joints or other similar openings. Common applications include enhancing the connection of polyethylene to steel ducts in external tendons, and between steel ducts cast into pier segments of precast segments. Shrink sleeves should be in accordance with Section 4.3.7 of “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12).

2.3.2.11 Diabolos

Diabolos are curved pathways cast into precast segmental deviators and/or pier segment diaphragms that allow external tendons to pass through without the need for connecting to an embedded rigid steel duct. The curved pathways flare at each end to accept a range of angle changes in tendon geometry. Diabolos are created either by casting a permanently embedded diablo pipe into the segment, or through the use of reusable diablo form inserts.

Where diabolos offer an alternative solution to calculating and detailing individual tendon pipe bends, they are structurally different from individual pre-bent pipes that bear evenly over a uniform radius. The actual contact length in diabolos varies, and may be quite short, depending upon the minimum radius of the deviator flare.

Figure 2.11 illustrates the difference in bearing and contact between pre-bent pipes and diablo deviators. Figure 2.12 shows reusable diablo form inserts used for the Phase 1 Dulles Corridor Metrorail Project in Tysons Corner, VA.

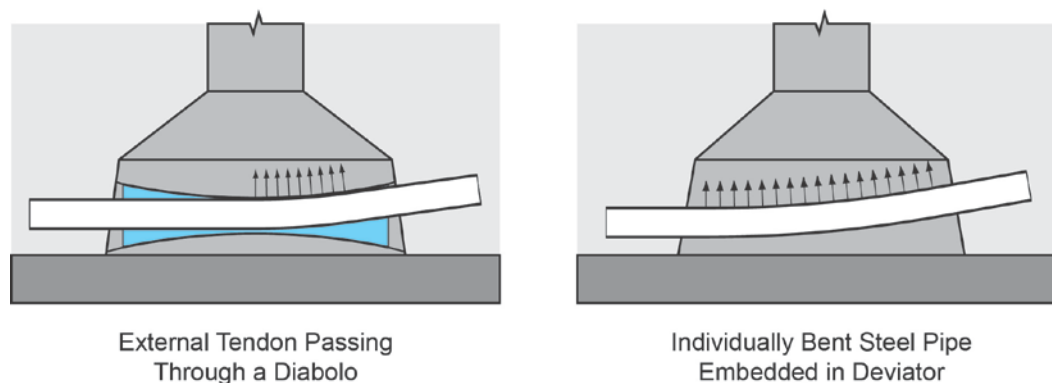


Figure 2.11 - Pressure Distribution: Diabolos vs. Steel Pipe



Figure 2.12 - Reusable Diabolo Inserts at Deviation Segment

2.3.3 Shipping, Handling and Storage of Ducts

Spiral-wound duct made from galvanized strip steel may be prefabricated or fabricated on site as necessary. Plastic duct may be shipped in coils or in bundles of straight lengths.

In order to avoid inadvertent introduction of contaminants or debris, it is recommended that the ends of duct coils or bundles be protected and covered during shipping and storage. Special temporary end caps may be used to seal the ends of individual ducts. Plastic ducts should be protected from sunlight, and ultraviolet degradation, and all ducts protected against crushing and excessive bending until installed in the bridge. All ducts and pipes should be stored in a dry location, on a raised platform, protected from weather and contamination.

2.3.4 Acceptance of Duct Materials

All duct materials (metal or plastic) ducts should comply with the requirements of AASHTO LRFD Bridge Construction Specifications and meet the requirements of Sections 4.4.3 and 4.4.4 of “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12).

2.3.5 Acceptance of Post-Tensioning System

Post-tensioning systems should be approved in accordance with Section 4.4.4 “Guide Specification for Grouted Post-Tensioning” (PTI/ASBI M50.3-12).

For acceptance and approval of a post-tensioning system, all components’ tests and results of post-tensioning system approval tests should be carried out by an independent approved body or testing laboratory. This testing should be completed prior to submission of Shop Drawings and other related documents to the Engineer for approval.

It is recommended that a system supplier provide full documentation including:

- Technical documents and drawings of general assembly of the system and details of components.
- Instructions and method statements for installation, stressing and grouting.
- A quality assurance plan covering production, shipping, handling, storage and installation of the system.
- Instructions for surveillance and maintenance of the system in service.

On site, the Contractor should maintain a complete record of all documentation, test reports, shipping dockets and approvals. Copies should be provided to the Inspector (CEI) to ensure compliance.

2.4 Grout

2.4.1 Purpose

Cement grout is chemically basic and provides a passive environment around the post-tensioning bars or strands. The grout also serves to bond internal tendons to the structure. Appropriate protection of post-tensioning tendons begins with complete filling of the ducts with high quality grout.

Post-Tensioning Institute document “Specification for Grouting of Post-Tensioned Structures,” PTI M55.1-12, is an excellent resource for the grouting of tendons. This specification delineates four classes of grout that can be used for most post-tensioning applications. These four classes of grout and their recommend exposure conditions are:

Class A – Nonaggressive: indoor or nonaggressive outdoor.

Class B – Aggressive: subject to wet/dry cycles, marine environment, deicing salts.

Class C – Nonaggressive or aggressive (pre-packages)

Class D – Determined by Engineer

Refer to Section 3.3 of “Specification for Grouting of Post-Tensioned Structures,” PTI M55.1-12, for further information concerning grout classifications.

2.4.2 Cement and other Pozzolans for Grout

The primary constituent of grout is ordinary Portland cement (Type I or II) that meets the requirements of ASTM C150/C150M. Other cementitious material may be added to enhance certain qualities of the final product. Fly ash and slag cements can improve corrosion resistance in aggressive environments. The addition of dry silica fume (micro-silica) can improve resistance to chloride penetration because the particles help fill the interstices between hydrated cementitious grains thus reducing the permeability. When used, these pozzolan admixtures should meet the following requirements:

- Fly Ash - Class C and Class F conforming to ASTM C618.

- Slag Cement - Conforming to ASTM C989/C989M. Only Grade 120 slag shall be specified for use in post-tensioning grouts.
- Silica Fume - Conforming to ASTM C1240. Densified silica fume shall not be used.

The water-cementitious material ratio should be limited to a maximum of 0.45 to avoid excessive water retention and bleed and to optimize the hydration process. Any temptation to add water to improve fluidity on-site must be resisted at all times. Fluidity may be enhanced by adding a high range water-reducer, HRWR, (Type F or G).

2.4.3 Admixtures

Grouts made of only cement and water often exhibit segregation and voids due to excessive bleed water. Like concrete, admixtures may be used to improve workability and reduce the water required, reduce bleed, improve pumping properties or entrain air. Care must be exercised to use the correct quantities in the proper way according to the manufacturer's instructions and to remain within the mix properties established by qualifying laboratory tests.

Calcium nitrite may help improve corrosion resistance in some situations by bonding to the steel to form a passive layer and prevent attack by chloride ions. The use of calcium nitrite may influence other properties such as setting time and strength.

High range water reducer (HRWR) improves short term fluidity. However, a grout with HRWR may lose fluidity later when being injected through hoses and ducts. Unlike a concrete mix, it is not possible to re-dose a grout especially when it is in the pump, hoses and ducts. Also, HRWR tends to cause bleed in grouts. On-site grout mixing with HRWR is not recommended.

Other admixtures include: Set Controlling, Air Entraining, Anti-Bleed, Expansion Creating, and Corrosion Inhibiting.

The addition of these should be strictly in accordance with manufacturer's recommendations. Furthermore, the mix should be qualified by appropriate laboratory testing. On site, daily grout production must be monitored by various field tests in order to maintain quality control and performance.

2.4.4 Pre-bagged Grouts

Grouts where the constituent materials are measured and batched on site do not always have uniform properties. This arises from variations in materials, day to day mixing differences, crew changes, weather conditions, and so forth. In an endeavor to eliminate problems related to grout variations, several State DOT's have obtained greater quality control by requiring "pre-bagged" grouts. In a pre-bagged grout, all the constituent materials have been thoroughly mixed and blended at the factory in the dry condition. This ensures that nothing other than water needs to be added while mixing on site.

A manufacturer of a pre-bagged grout may already have had the material pre-qualified by a State DOT or other agency. In this case, it is appropriate to accept it on the basis of a written certification; providing that the manufacturer has on-going quality control tests that can be confirmed by submitting test reports to the Engineer. The certification should show the mixed

grout will meet the pre-qualified standard. On site, daily grout production must be monitored by various field tests in order to maintain quality control and performance.

2.4.5 Thixotropic vs. Non-Thixotropic Grout

A thixotropic grout is one that begins to gel and stiffen in a relatively short time while at rest after mixing, yet when mechanically agitated, returns to a fluid state with much lower viscosity. Most grouts made with cementitious materials, admixtures and water are non-thixotropic. Thixotropy may be exhibited by some, but not necessarily all, pre-bagged grouts.

A critical feature of a grout is that it should remain pump-able for the anticipated time to fully inject the tendon. This may be significant for long tendons or where a group of several tendons is to be injected in one continuous operation. Some thixotropic grouts can have very low viscosity after agitation, becoming easy to pump.

2.4.6 Laboratory Tests

Acceptance of a grout is usually based upon the results of laboratory tests. Laboratory tests on trial batches of the proposed grout using the same materials and equipment to be used on site are used to qualify a grout. Trial grout should be prepared by personnel experienced in preparing and testing grout mixes. This should be done at an approved material testing laboratory. All tests should be performed at temperature and humidity conditions expected on site. Trials should precede construction by at least eight weeks in order to allow time for testing and resolution of any concerns.

Laboratory tests typically performed on grouts are presented in the following sections. Refer to the "Specification for Grouting of Post-Tensioned Structures," PTI M55.1-12 for additional information. Testing of grouts previously prequalified through testing may be waived by the Design Engineer. Testing of prepackaged grouts shall be performed at the minimum and maximum water/bagged material ratios.

2.4.6.1 Setting Time

Grout set time is tested in accordance with ASTM C953 "Standard Test Method for Setting Time of Grouts." The setting time should be more than 3 but less than 12 hours. The tested setting time does not relate to the placement or working life of the mix.

2.4.6.2 Grout Strength

Grout cube specimens, 50mm (2 in), are prepared and tested according to ASTM C942 "Standard Test Method for Compressive Strength of Grouts." The strength should be 21MPa (3000 psi) at seven days and 35MPa (5,000 psi) at 28 days.

2.4.6.3 Permeability

Grout permeability should be tested in accordance with ASTM C1202 "Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." A value less than 2500 Coulombs after 6 hours is generally acceptable when subjected to a potential of 30 volts.

2.4.6.4 Volume Change

Volume change should be tested in accordance with ASTM C1090 "Standard Test Method for Measuring Changes in Height of Cylindrical Specimen from Hydraulic Cement Grout." A value of 0.0% to less than +0.1% at 24 hours and no more than +0.2% at 28 days is acceptable.

2.4.6.5 Pumpability and Fluidity (Flow Cone)

Grouts should be tested according to ASTM C939 “Standard Test Method for Flow of Grout, modified by filling the flow cone above the standard level, and measuring the time to fill a one-liter container. 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. It is recommended that some of the laboratory qualification tests be run at the ends of this spectrum.

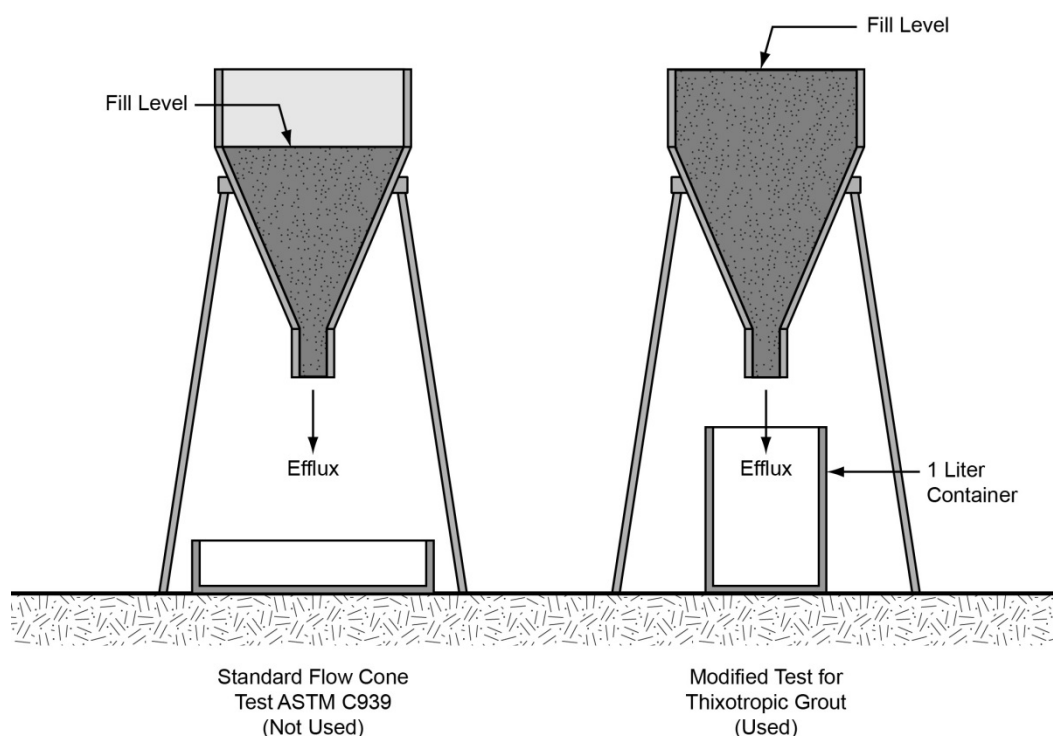


Figure 2.13 - Standard and Modified ASTM C939 Flow Cone Testing

2.4.6.6 Simulated Field High Temperature Fluidity Test

This non-standard test was developed by the Florida Department of Transportation to ensure that a mix remains sufficiently workable for pumping under simulated high temperature site conditions after re-circulating for a one hour period. The following procedure, taken from FDOT Standard Specification, Section 938, may be used for guidance:

- (a) Perform the test in a temperature conditioned laboratory. Condition the room, grout, water, duct, pump, mixer and all other equipment to be used to a temperature of 32.5°C (90°F) for a minimum of 12 hours prior to the test.
- (b) Use 122m (400 ft, \pm 3m (10 ft)) of duct (tube) for the test. Use a duct with an inside diameter of 25mm (1 inch).
- (c) Mix the grout to the specified water content. Pump the grout through the duct until the grout discharges from the outlet end of the duct and is returned to the pump.

- (d) Start the one hour test period after the duct is completely filled with grout. Record the time to circulate the grout through the duct. Constantly pump and re-circulate the grout into the commercial grout mixer storage tank.
- (e) Pump and re-circulate the grout for a minimum of one hour.
- (f) Record at 15 minute intervals throughout the test period, the pumping pressure at the inlet, grout temperature, and fluidity at the discharge outlet.

The result is satisfactory if the flow-cone efflux time (standard or modified ASTM C 939) after one hour of recirculation is not greater than 30 seconds.

2.4.6.7 Bleed

The “Wick Induced Bleed Test” involves immersing a 1000 mm (40 in) length of conditioned, clean, seven wire strand (either 0.5” or 0.6” in diameter) in a cylinder with a height of 1000 mm (40 in) and diameter of 80 mm (3 in), filled with 900 mm (35 in) of carefully prepared grout and following a modified version of ASTM C940 to record the bleed water above the grout as detailed in the Section 4.4.1 of “Specification for Grouting of Post-Tensioned Structures,” PTI M55.1-12. A bleed of 0.0% after 3 hours at normal ambient room temperature of approximately 20°C (68°F) is acceptable (Figure 2.14).

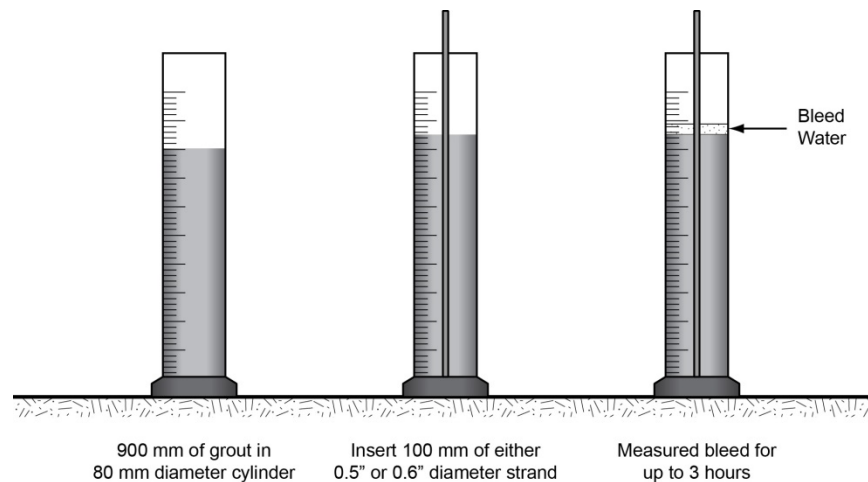


Figure 2.14 - Wick-Induced Bleed Test

The “Schupack Pressure Bleed Test” uses a Gelman Filter to retain grout particles and records the bleed water expelled under air pressure applied up to 0.34MPa (50 psi) (Figure 2.15). The test should be performed per ASTM C1741. Refer to Section 4.4.6.2 of “Specification for Grouting of Post-Tensioned Structures,” PTI M55.1-12 for additional test information and test limits.

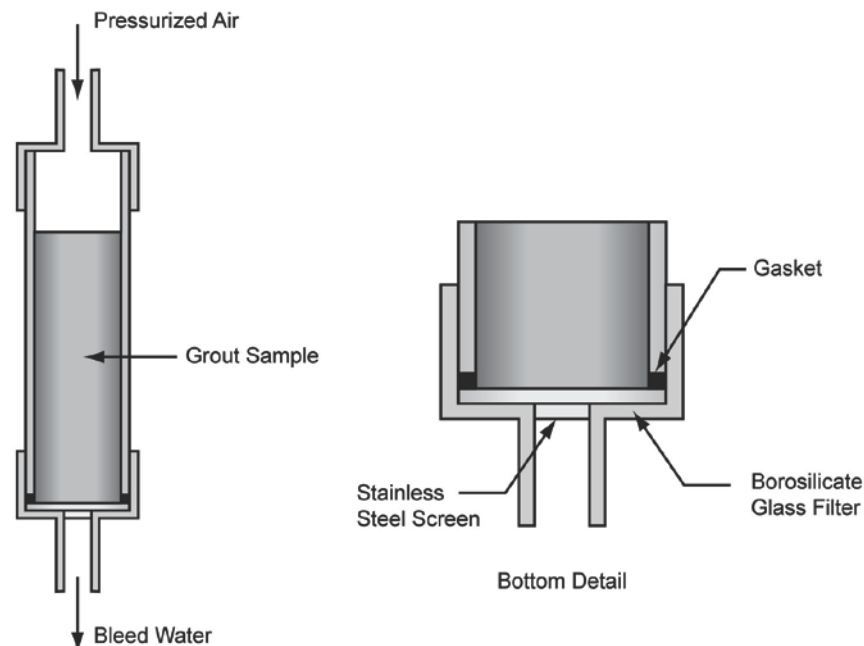


Figure 2.15 - Bleed Under Pressure Test (Gelman Filtration Funnel)

2.4.6.8 Corrosion

An Accelerated Corrosion Test (ACT) may be used to quantify the expected level of corrosion for a specific grout. The test is based on research made under FHWA-RD-91-092 which indicates that a mean time to corrosion of 1,000 hours when tested at 0.2V is suitable. This test is not yet standardized. However, it is particularly useful in determining combinations of admixtures that may adversely affect the corrosion protection performance of a grout. The maximum chloride content for grout is 0.08%.

2.4.6.9 Wet Density

A wet density value for grout should be established in the laboratory using an American Petroleum Institute Mud Balance (API Recommended Practice 13B-1: "Standard Procedures for Field Testing Water-Based Drilling Fluids") for the maximum and minimum recommended water dosage. The values determined from this testing should be compared to those provided by the Manufacturer.

Once this range has been established, wet density can be monitored in the field to ensure that grout water content is appropriate, using an American Petroleum Institute Mud Balance (API Recommended Practice 13B-1: "Standard Procedures for Field Testing Water-Based Drilling Fluids").

2.4.6.10 Inclined Tube Test

The inclined tube test shall be performed in accordance with EN 445 “Grout for Prestressing Tendons – Test Methods,” produced by the American National Standards Institute. Grout bleed should not exceed 0.3% of the initial volume of the grout after being kept at rest for 3 hours.

2.4.7 Shipping, Handling, Storage and Shelf-Life

Cement and other materials may be delivered in bags but should be stored in a weatherproof building. Storage in the open may be allowed providing that materials are on a raised, dry platform with adequate weatherproof covering. Additives should be stored in a warm environment. Dissolvable packaging materials should not be allowed for any components as they can break down to pulp and cause equipment or duct blockage.

It is essential that the Contractor maintain a record of all delivered materials. A copy of the manufacturer’s quality control data sheet should accompany each LOT of grout components shipped to the site. A LOT is that parcel of material from the same production run shipped to the site. Each shipment should be clearly identified with the corresponding LOT number so that it can be tracked to the manufacturer’s quality control records. Copies of shipment records and quality control test reports should be maintained by the Contractor and copies provided to the Construction Inspector.

Prior to use, all materials in storage should be checked to make sure they have not exceeded the manufacturer’s shelf life or have not absorbed moisture and begun to clump or hydrate. It is recommended that cementitious materials and pre-bagged grouts not be stored on site for more than one month before they are used.

Dry silica fume is available in bags. Special care is essential when mixing dry silica fume with cement and additives in order to produce a job-site grout mix, as it can lead to clumping and a poor result. Pre-bagged grouts containing silica fume have been dry blended and do not exhibit this problem.

Any material with a total time from manufacture to use in excess of six months should be retested, or recertified by the supplier before use or else be rejected and replaced. Approval of any grout or grout materials by the Construction Inspector should not preclude subsequent rejection if material is damaged in transit or later found to be defective for any reason.

2.4.8 Acceptance

A proposed grout is normally accepted on the basis of the laboratory tests listed in Section 2.4.6 performed before construction, or on the basis of certification from the manufacturer that the (pre-bagged) grout materials meet the pre-qualification requirements of the Owner or project specifications. The manufacturer should have a continuing quality control program to ensure that production continues to meet the specified requirements. Copies of certificates should be checked and a record kept by the Contractor and the Construction Inspector. Use of a particular grout on site may continue providing that certification and documentation is kept up to date, that materials in storage remain usable and that daily grout mix production tests meet specified limits. Approval to use a grout should be withdrawn if these quality control standards are not maintained.

2.4.9 Field Mock-Up Tests

When specified in the Contract Documents, field mock-up tests may be used to demonstrate that materials, components such as inlets and outlets, mixer, pumping and grout injection methods will result in complete filling of a duct. Mock-ups are appropriate for new means and methods, new types of components or grout materials. Production tendons should not be used for the mock-up test.

Mock-up Tests should be in accordance with Section 4.7.2 of “Specification for Grouting of Post-Tensioned Structures,” PTI M55.1-12. As far as possible, a mock-up should simulate the type and size of tendon, duct, anchorages and proposed attachments and be arranged to a similar, representative, geometric duct profile. The following field mock-up tests are suggested for guidance:

(A) For continuously draped tendons in spliced girders or cast-in-place construction: one tendon mock-up of the longest tendon from anchor to anchor, including all proposed intermediate duct couplings and grout inlets and vents. The profile should simulate the tendon with the maximum accumulated curvature from anchor to anchor.

(B) For cantilever or continuity internal and external tendons in precast or cast-in-place segmental construction: one tendon mock-up of the longest tendon from anchor to anchor, including all proposed intermediate duct couplings and grout inlets and vents. The profile should simulate the tendon with the maximum accumulated curvature from anchor to anchor.

(C) For vertical tendons: one tendon mock-up of the longest tendon from anchor to anchor, including all proposed intermediate duct couplings and grout inlets and vents. The profile should simulate the tendon with the maximum accumulated curvature from anchor to anchor.

The following tests should be conducted and satisfied during the field mock-up trials:

- Pumpability and Fluidity (Flow Cone) (2.4.6.5)
- Simulated Field High Temperature Fluidity Test (2.4.6.6 - Optional)
- Wick Induced Bleed Test (2.4.6.7)
- Wet Density (2.4.6.9)
- The Schupack Pressure Bleed Test (2.4.6.7) should be satisfied for projects where longitudinal tendons have a maximum difference in height at any point over 6 feet or vertical tendons are over 20 feet high.

2.5 Other PT System Qualification Tests

Project specific documents should state when a dynamic system qualification test for unbonded (external) tendons is necessary. This should comply with the most recent AASHTO LRFD Bridge Construction Specifications. In the absence of any other information, for guidance, reference may be made to “Acceptance Standards for Post-Tensioning Systems,” PTI, 1998.

This Page Intentionally Left Blank.

Chapter 3 – Post-Tensioning Duct and Tendon Installation

This Chapter 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 competition 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 all plan reinforcement and 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 or Construction Inspector (CEI). 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. Shop drawings should also include corrosion protection details and designate the level of protection achieved, as defined in "Guide Specification for Grouted Post-Tensioning," PTI/ASBI M50.3-12.

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).
- Segmental Duct Couplers (if used).
- 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.
- Segmental Duct Couplers (if used).
- 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 (μ) and wobble coefficient (k).
- The estimated elongation and maximum jacking force for each tendon.
- The estimated anchor 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

A typical shop drawing submittal, review and approval process for a Design-Bid-Build project is illustrated in Figure 3.1. Typical responsibilities associated with this approach to shop drawings include:

- **Contractor:** Arrange for the preparation of the necessary shop drawings and other relevant information required by the Contract. Receive and review shop drawings from Suppliers, Manufacturers, and the Contractor's Engineer. Submit shop drawings to the Owner in accordance with the project plans and specifications. Coordinate distribution of approved shop drawings or return shop drawings for changes and resubmittal.
- **Contractor's Engineer:** Prepares post-tensioning related calculations and shop drawings on behalf of the Contractor.
- **Engineer (Designer):** Receives post-tensioning calculations and shop drawings from the Owner (often the Contractor makes simultaneous submissions to the Owner and Engineer in order to expedite approvals.) Reviews submittals for compliance with the information shown on the plans. Approves (completely or "as noted") or rejects the submittal and returns the submittal to the Owner. Forwards a copy of the information transmitted to the Owner to the Construction Inspector (CEI).
- **CEI – Construction Engineering and Inspection:** Receives notice of shop drawing submittal from the Contractor. Receives and reviews the Engineers return of the shop drawing. Represents the interest of the Owner on the job-site (Resident Engineer).

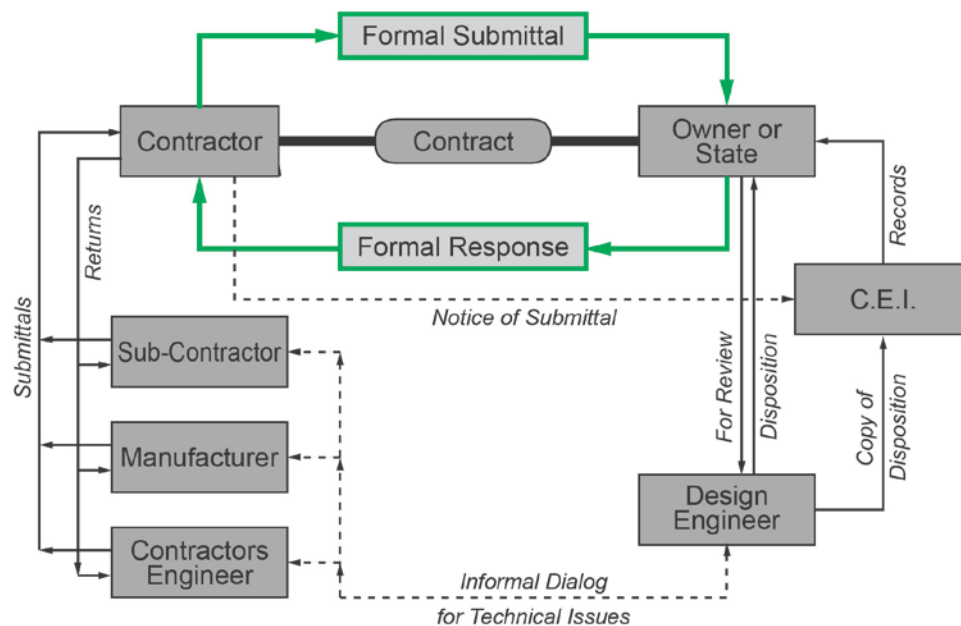


Figure 3.1 - Typical Shop Drawing Approval Process for Post-Tensioning

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, anchor 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 Contractor's 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 developed for subsequent tendon stressing.

Friction losses along the length of the tendon, between anchorages, are attributed to two sources. The first of these frictional losses is the result of the expected friction between tendon and duct as the profile of the tendon changes. These losses are related to angular changes in the tendon profile. The top sketch in Figure 3.2 shows the trajectory of a tendon within a desired duct profile. The friction coefficient (μ) is defined to predict losses of this type. The value of the friction coefficient is a function of the duct material.

Predicting frictional losses along the length of a tendon using the friction coefficient alone does not typically correlate well with field results. Another coefficient of frictional loss, wobble (k), is used to account for additional friction between strand and duct as a result of unintended duct misalignments. The concept of duct wobble is shown in the bottom sketch of Figure 3.2.

The equation relating tendon force at a point along the length of a tendon, as a function of friction and wobble determined from the formula:

$$P(x) = P_{jack} \cdot e^{-(\mu\theta+kx)}$$

Equation (3.1)

Where: x = distance along length of tendon where tendon force is being evaluated
 $P(x)$ = Force in tendon at a distance x along tendon length
 P_{jack} = Stressing force at anchorage
 μ = friction coefficient
 K = wobble coefficient
 θ = total angular change from stressing end to point x

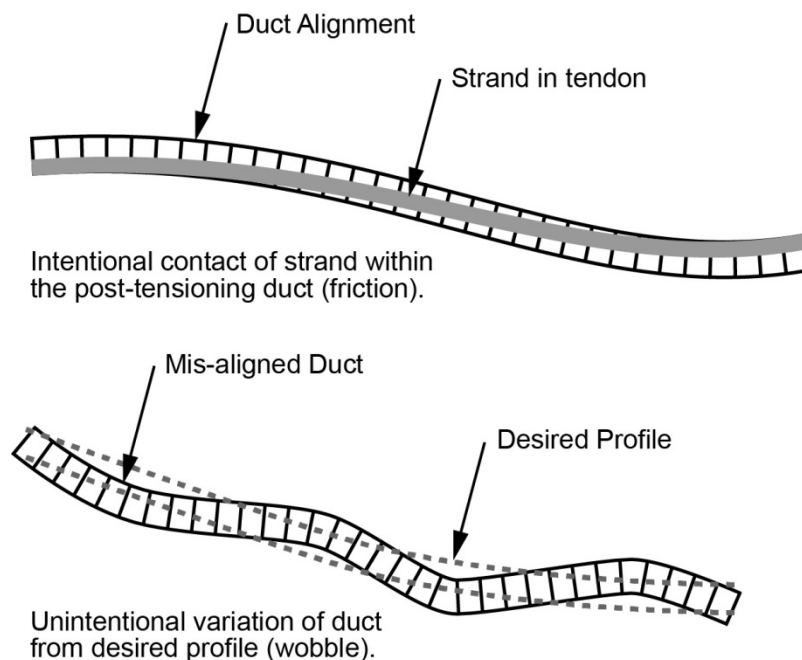


Figure 3.2 - Frictional Losses Related to Friction and Wobble

Anchor 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 anchor set occurs again at the jacking end. Since the load is picked up again upon re-gripping, the anchor set of individual pulls is not cumulative. Only the final anchor set affects the loss of tendon force. However, keeping account of cumulative elongations and anchor set during repeated pulls by a jack is always helpful for resolving unforeseen problems.

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 spans, friction loss may be so significant that it is essential to stress the tendon from both ends to ensure adequate force throughout.

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 tendon forces and elongations are defined as follows:

- Length of tendon (L)
- Assumed area of tendon (A)

- Modulus of Elasticity assumed (E)
- 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 ($\theta(x)$)
- Length of portion of tendon between two points “i” and “j”, = x_{ij}
- Anchor seating loss (W)
- Friction in anchor (%)
- Friction in jack (%)
- P_{jack} = force at the jack

Typical values for friction and wobble coefficients are provided in Table 5.1 of “Guide Specification for Grouted Post-Tensioning”, PTI/ASBI M50.3-12. Section 5.4 of the same guide specification provides typical values for the modulus of elasticity of the post-tensioning steel.

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:

$$\Delta L = \sum \frac{P_{ave} \cdot x_{ij}}{A_s \cdot E_s}$$

Equation (3.2)

Where: P_{ave} = average force over x_{ij}

Stressing calculation information should be forwarded to the site engineer or inspector. This information should include:

- Tendon identification
- Assumed area of strands (A)
- Assumed modulus of elasticity (E)
- Required jacking force, P_{jack}
- Anchor set (W) assumed for each end of each tendon
- Calculated elongation at each end, before release of the jack and anchor set for each end of the tendon, depending upon the ends to be jacked first and second
- The anticipated total elongation, ΔL , before anchor set

Calculations of tendon force and elongation are made using assumed values for the tendon area (A) and modulus of elasticity (E). If elongations measured during stressing operations are outside of tolerances, actual values of A and E for the particular reel of strand should be used to resolve discrepancies.

3.1.2.1 Example 1: Four-Span Girder

Consider the four-span girder bridge with spans of 135'-180'-180'-135' as shown in Figure 3.3. Two spans of the bridge and the profile of a tendon which is made up of parabolic segments are shown in Figure 3.4. Calculate the forces along the length of the tendon and the expected

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

elongations accounting for friction, wobble, and anchor set. The tendon is made of 12-0.5" diameter strands, giving it a cross sectional area of 6.24 in². The tendon is stressed from both ends, first at End A and then End B. The stressing force is 1264 kips (75% f_{pu}). The modulus of elasticity of the tendon is 28,000 ksi. The friction coefficient is 0.25 and the wobble coefficient is 0.0002ft/ft.

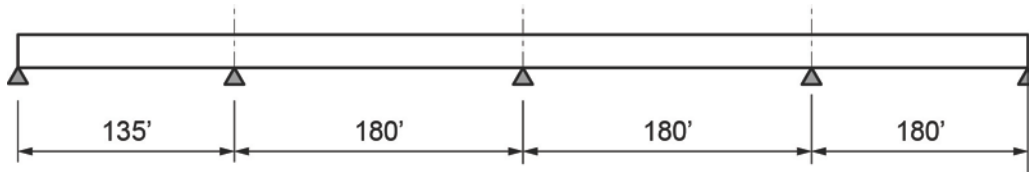


Figure 3.3 - Four-Span Girder

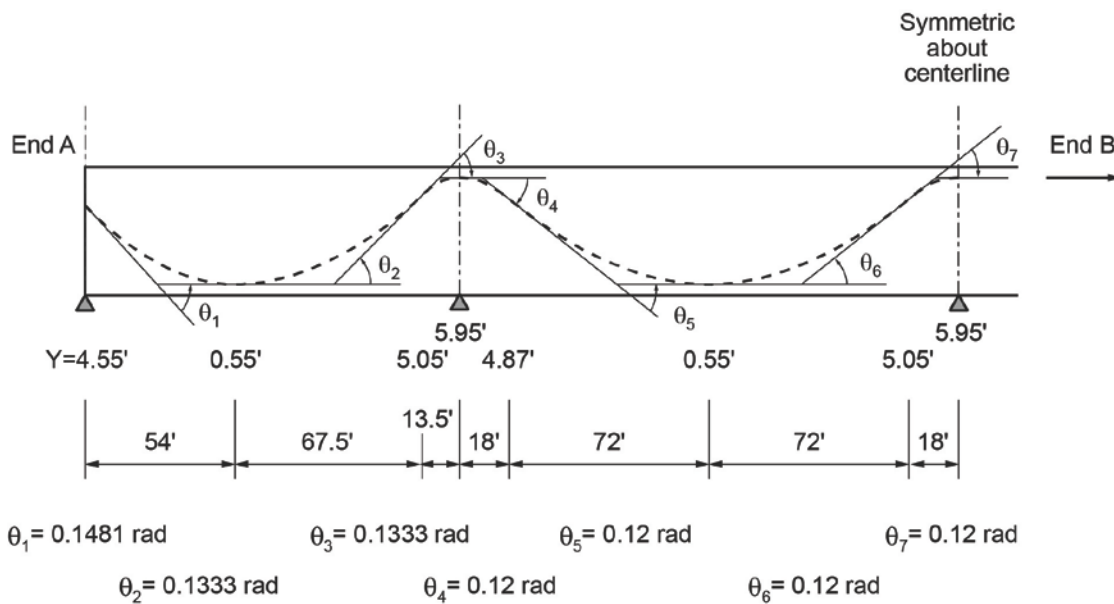


Figure 3.4 - Tendon Geometry

The calculation is made by considering each arc of the profile in turn and applying Equation 3.1 to determine the force at the beginning and end of each segment of tendon length. The calculation begins at the stressing end and continues across the length of the tendon. Table 3.1 shows a table of the results of these calculations. The total elongation is found by summing the last column of the table in Table 3.1. For this example, the total elongation is calculated to be 41.62 inches.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Section	x	Δh	$\Delta\theta$	Δ Loss Segment (%)	Δ Loss (%)	Force (kips)	Segment Elongation (inches)
1	0.0	0.00	0	1.00	1.00	1264	0.00
2	54.0	4.00	0.1481	0.9533	0.9533	1205	4.58
3	67.5	4.50	0.1333	0.9542	0.9097	1149	5.46
4	13.5	0.90	0.1333	0.9646	0.8775	1109	1.05
5	18.0	1.08	0.1200	0.9670	0.8485	1072	1.35
6	72.0	4.32	0.1200	0.9566	0.8116	1026	5.19
7	72.0	4.32	0.1200	0.9566	0.7764	981	4.96
8	18.0	1.08	0.1200	0.9670	0.7507	949	1.19
9	18.0	1.08	0.1200	0.9670	0.7259	917	1.15
10	72.0	4.32	0.1200	0.9566	0.6944	877	4.44
11	72.0	4.32	0.1200	0.9566	0.6642	839	4.24
12	18.0	1.08	0.1200	0.9670	0.6423	812	1.02
13	13.5	0.90	0.1333	0.9646	0.6196	783	0.74
14	67.5	4.50	0.1333	0.9542	0.5912	747	3.55
15	54.0	4.00	0.1481	0.9533	0.5636	712	2.71

Table 3.1 - Example 1 Tendon Force and Elongation Calculation

Two observations are made with regard to the calculated total elongation. First, this elongation is greater than the available stroke of normal stressing jacks. As a result, obtaining the full elongation will require several separate pulls from End A. The calculations reflected in Table 3.1 do not consider the initial anchor set at End B. This anticipated anchor 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 $41.62 + 0.375 = 41.995$ in. - if anchor 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. Typically an initial load, typically 20%, is applied at A to remove slack and seat the wedges at End B. Elongations are typically measured after this initial load. A correction is added for the initial 20% based upon that measured from 20 to 100% load.

Table 3.1 shows a graph of the tendon force along the length of the tendon when the tendon has been stressed to the full jacking force. Note that the area below the tendon force curve is equal to the work to elongate the tendon. Dividing this area by the tendon area and modulus of elasticity produces the elongation of the tendon when stressing at End A.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

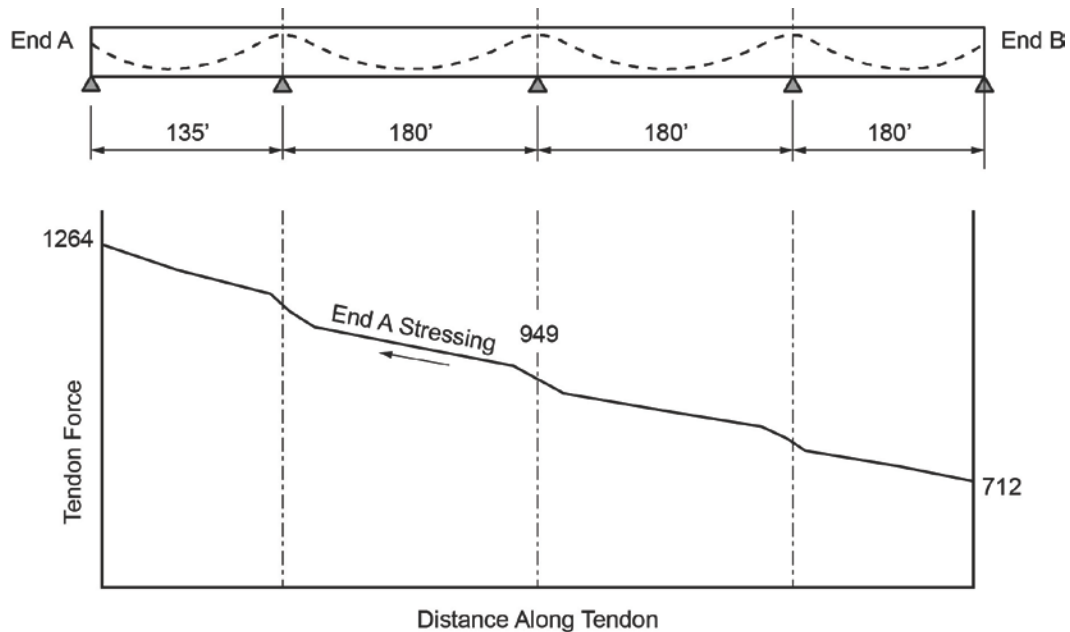


Figure 3.5 - Tendon force Diagram for Stressing at End A

When the jacking force is reached at End A, the wedges are made snug and the tendon force released. The tendon draws the wedges, or seats them, into the wedge plate. Values of wedge can vary with post-tensioning system, but a typical value is 3/8 inch. As the wedge seating is being seated the tendon is shortening, reducing the tendon force at the wedges. Only a portion of the length of the tendon may, however, be affected by the anchor set. This is because the work to seat the wedges is typically much less than the work done to elongate the tendon.

Figure 3.6 shows the effect of an anchor set of 0.375 inches on the forces along the length of the tendon after stressing at End A. The shaded area in Figure 3.6 represents the work performed during the anchor seating. This area is determined by finding a point along the length of the tendon to a location where the anchor set does not impact the tendon stressing force (point of zero movement). Working back from the tendon force at that point to the anchorage, the loss in tendon force is related to the geometry of the tendon, friction and wobble, just as when originally stressed. A typical simplification for this calculation is to mirror image the force loss diagram about a horizontal line passing through the point of zero movement.

For this example, the point of zero movement was determined by trial and error to be 75.2' from the stressing end. The force at the point of zero movement is 1187.5 kips, and the force at the anchorage with anchor set loss is 1111 kips. The convergence on these values was found by equating the shaded area in Figure 3.6, divided by the tendon cross sectional area and modulus of elasticity, to the anchor set of 3/8":

Equation (3.3)

$$Set = \frac{((94.0k \cdot 54') + (17.5k \cdot 21.2'))12}{(6.24in^2)(28,000ksi)} = 0.374" \approx 0.375"$$

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

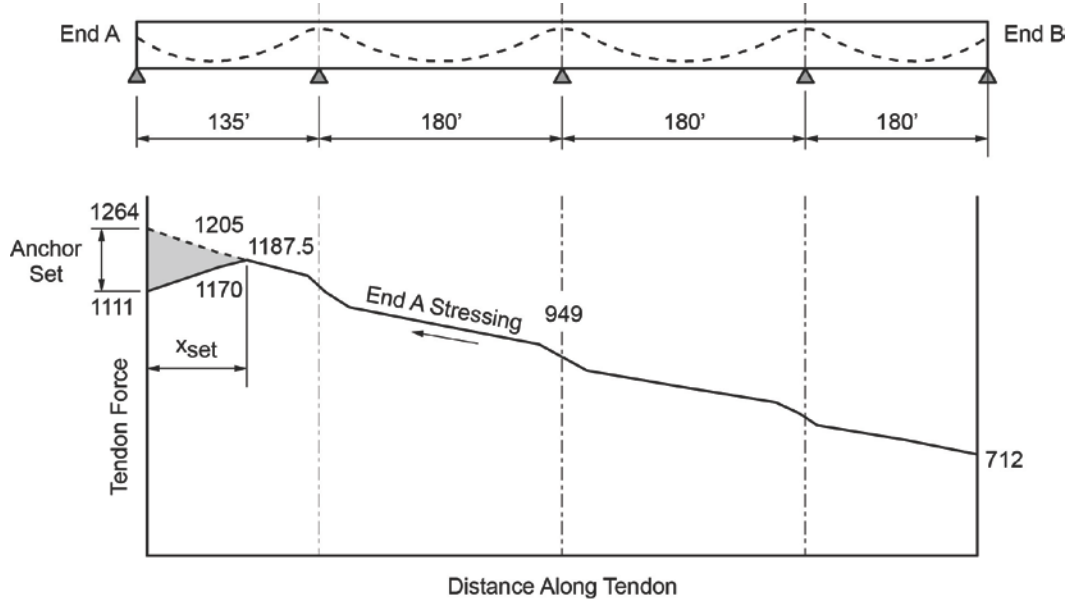


Figure 3.6 - Tendon Force Diagram after Anchor Set at End A

The second stage of stressing is now performed from End B. After stressing from End A, the force in the tendon at End B is calculated to be 712 kips. When jacking at End B, the jack will not begin to move until the load exceeds this amount. The jack at End B will pick up load at 712 kips and continue to the final jacking force of 1264 kips, effecting the force in the tendon 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 of the tendon, over the middle pier.

The shaded area shown in Figure 3.7 between the two tendon force diagrams, divided by the tendon area and modulus of elasticity is equal to the elongation due to stressing the tendon at End B. For this example the tendon elongation due to second stage stressing is 5.93 inches.

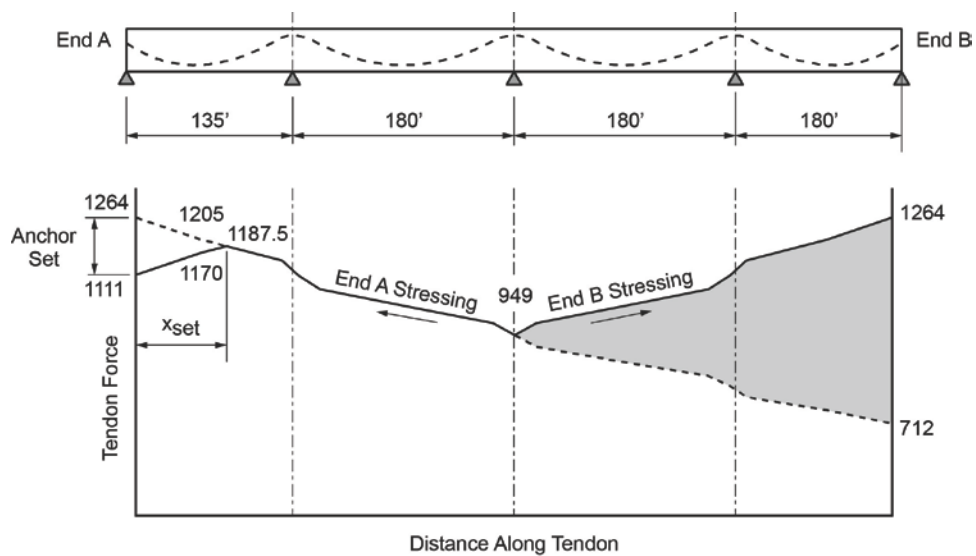


Figure 3.7 - Tendon Force Diagram after Stressing from End B

The final change in tendon force is a result of the anchor set at End B. By symmetry of the tendon and jacking force, the resulting loss due to anchor set is the same that was computed at End A. This loss and the final tendon force diagram after stressing is shown in Figure 3.8.

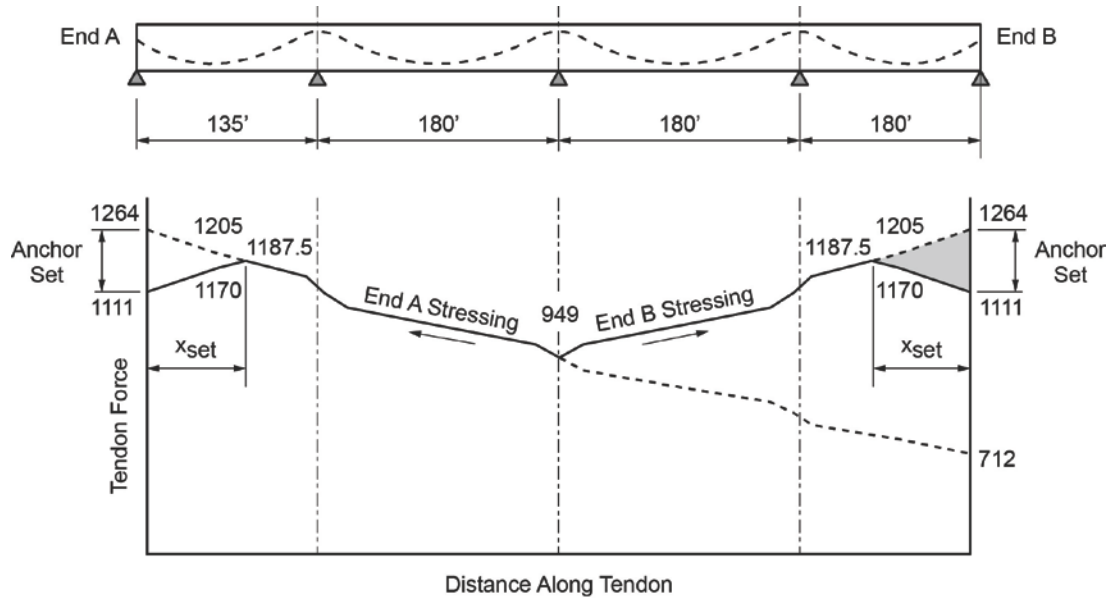


Figure 3.8 - Tendon Force Diagram after Anchor Set at End B

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:

Consider an average force in the tendon of 960 kips while stressing from End A. Also consider a girder cross sectional area of 80 ft^2 , a bridge length of 630 feet, and a modulus of elasticity of concrete of 650,000 ksf. The elastic shortening of the bridge during the stressing of the tendon from End A would be 0.14 inches.

This amount of elastic shortening is 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. 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 3.9). Calculate the forces along the length of the tendon and the expected elongations accounting for friction, wobble, and anchor set. As with Example 1, the tendon is made of 12-0.5" diameter strands, giving it a cross sectional area of 6.24 in². The tendon is stressed from the right end only. The stressing force is 1264 kips (75% f_{pu}). The modulus of elasticity of the tendon is 28,000 ksi.

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, but there is no loss due to wobble in external tendons, so $k = 0.0$.

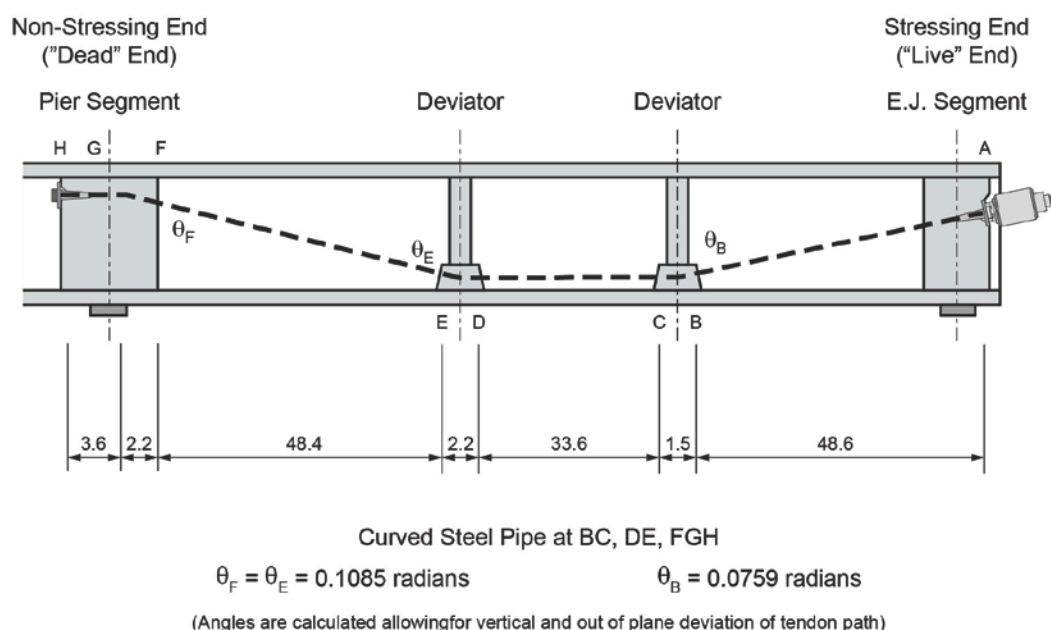


Figure 3.9 - External Deviated Tendon in End Span

As with Example 1, the calculation for tendon force and elongation is made by considering each angular change in turn and applying Equation 3.1 to determine the force at the beginning and end of each segment of tendon length. The calculation begins at the stressing end and continues across the length of the tendon. Table 3.2 shows a table of the results of these calculations. The total elongation is found by summing the last column of the table in Table 3.2. For this example, the total elongation is calculated to be 11.87 inches.

3.2 Tendon Testing On Site

On-site testing may be required to establish or confirm design parameters related to the post-tensioning tendons. Procedures for two of these tests, friction evaluation and modulus of elasticity evaluation, are provided in the following Sections.

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. 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, 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, 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 anchor set 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 anchor set (wedge 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. 3.11). The force and elongation may not immediately return to zero due to residual friction effects.

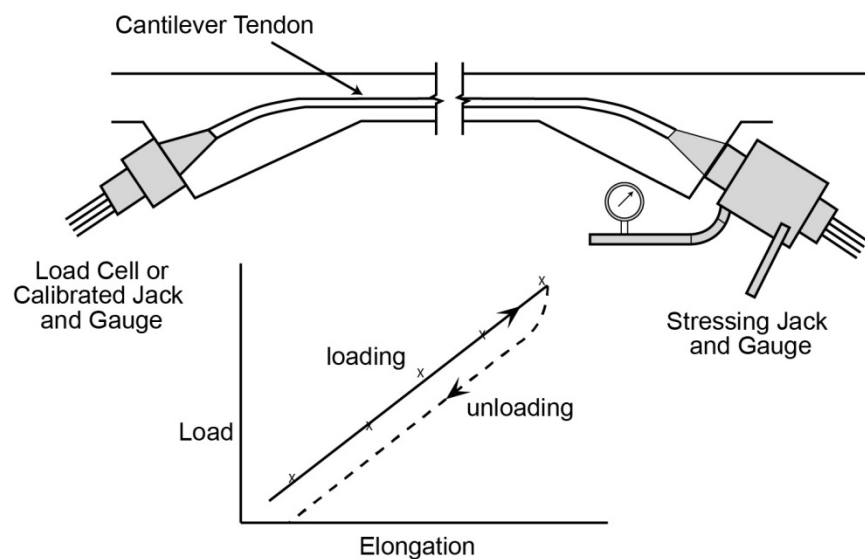


Figure 3.11 - On-Site Friction Test

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.

The strands must be removed after completion of the friction test in order to remove the load cell, and the strands cannot be reused due to wedge “bite marks” on the strands.

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.

In the event that field results for tendon elongations are not within tolerances, and resolution with stressing calculations cannot be achieved by another means, the modulus of elasticity of the tendon may be evaluated by bench test. 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 3.12 which may be used for guidance if the project documents require bench tests.

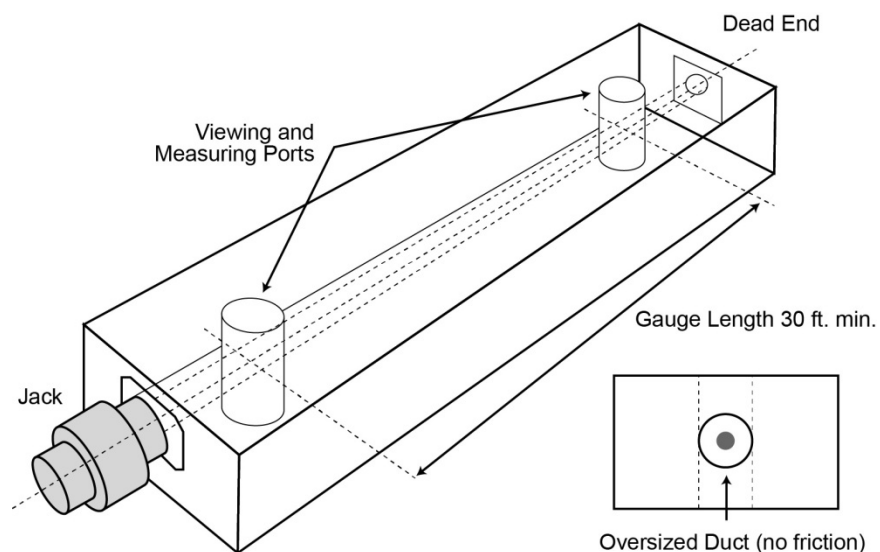


Figure 3.12 – On-Site Bench Test for Modulus of Elasticity

3.3 Anchor Installation

3.3.1 Anchorages

Anchorages should be firmly attached to bulkheads so that they do not move during casting of the surrounding concrete. The orientation of the anchorages should be within two degrees of their orientation shown on the post-tensioning shop drawings. Trumpets should be perpendicular to anchorages and firmly attached. Connections of the anchorages to the ducts should be made in accordance with the protection level as recommended in “Guide Specifications for Grouted Post-Tensioning”, PTI/ASBI M50.3-12. Grout injection ports and inspection vents should be attached to the anchorages and supported to maintain their functionality after the surrounding concrete is cast.

3.3.2 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 3.13). 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.

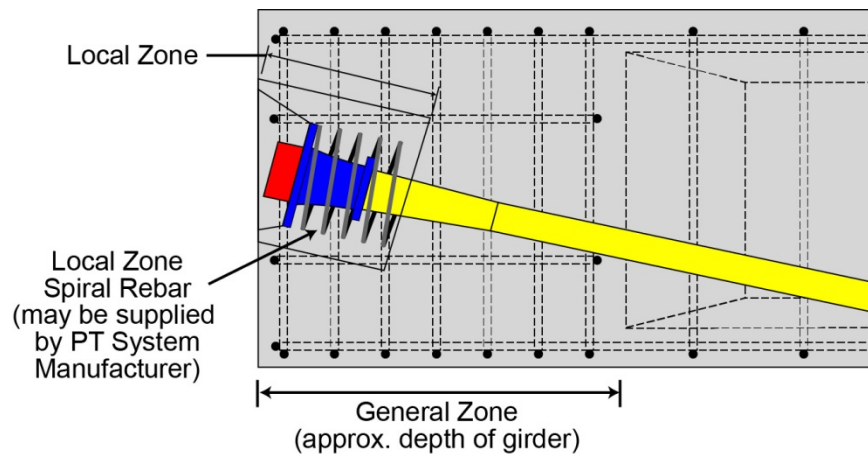


Figure 3.13 - General and Local Anchor Zone in End of I-Girder

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 3.14).

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.

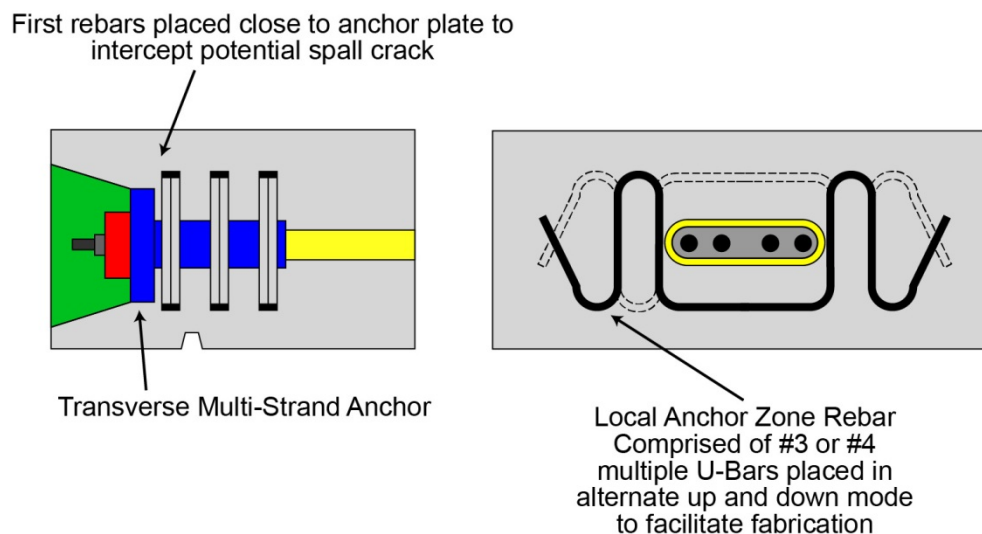


Figure 3.14 - Local Zone Reinforcing for Edge Anchor in Thin Slab

AASHTO LRFD Section 5.10.9.7.3 should be consulted when detailing local and general zones of reinforcing:

"Local zone reinforcement supplied as part of a proprietary system shall be shown on post-tensioning shop drawings. Adjustment of general zone tensile reinforcement due to reinforcement supplied as part of a proprietary system may be considered as part of the shop drawing approval process. The responsibility for design of general anchorage zone reinforcement shall remain with the Engineer of Record."

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, Section 5.10.3.3 through 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.
- Use mandrels to maintain alignment of the ducts during casting across the joints between precast segments in segmental construction.

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

Recommendations for ducts in concrete in I-girders (Figure 3.15):

- 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 and to permit insertion of concrete vibrators.
- Provide a clear distance equal to a duct diameter.

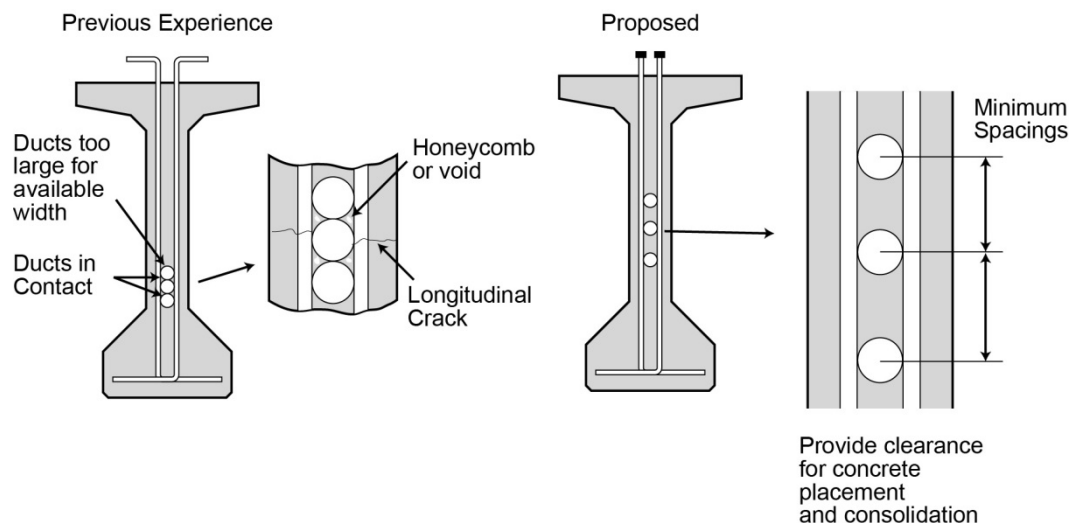


Figure 3.15 - Duct Spacing and Clearance in Post-Tensioned Precast Girders

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. Typical features to be checked for transverse tendons are shown in Figure 3.16. The details shown in this Figure are also applicable to the checking of longitudinal tendons.
- Provide a clear distance equal to a duct diameter.

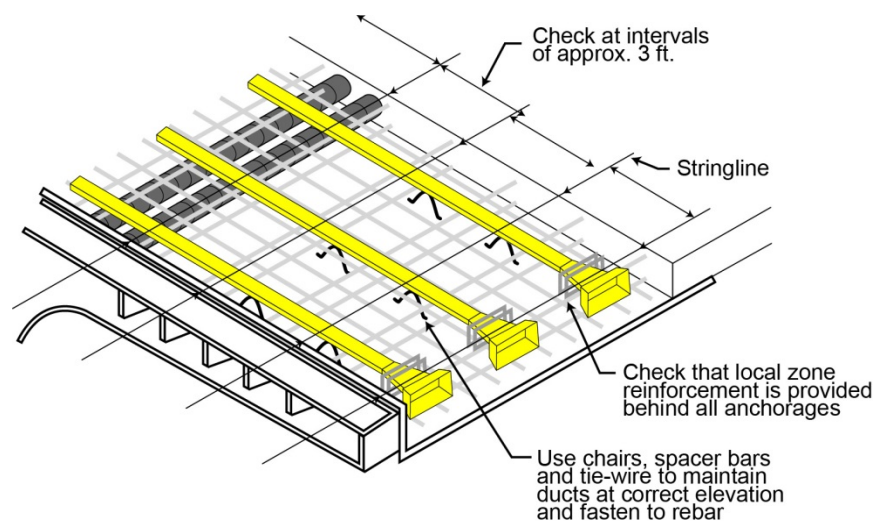


Figure 3.16 - Check Longitudinal and Transverse Duct Alignments

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.
- In the case where split pier segments are used, with external tendons passing through the joint to an anchorage, the 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.

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. 3.17.

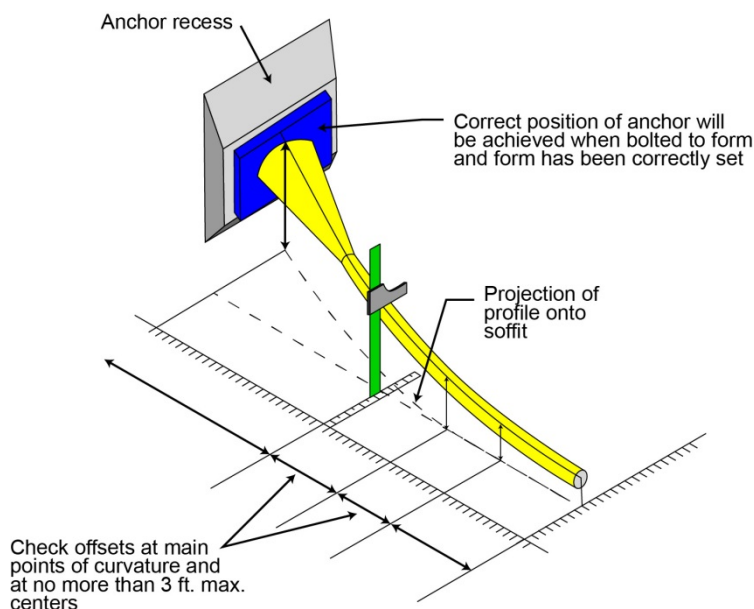


Figure 3.17 - Anchor Recess and Checking of Duct Alignment

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

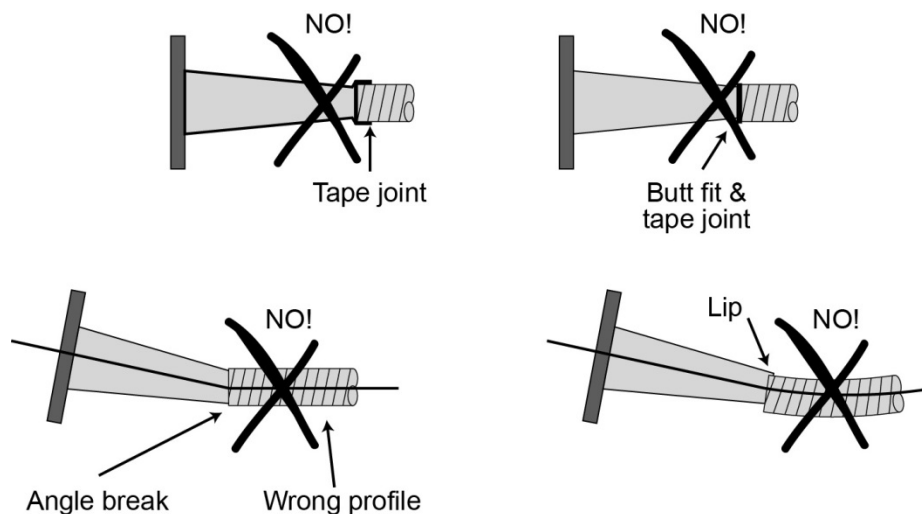


Figure 3.18 - Unacceptable Duct Connections and Mistakes

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 3.19).

- 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 48" for steel pipes, 48" for round galvanized metal ducts, 24" for round plastic ducts, 24" for flat plastic ducts with strand preinstalled, or per recommendations of duct supplier.
- Minimum cover and clearances should be maintained.

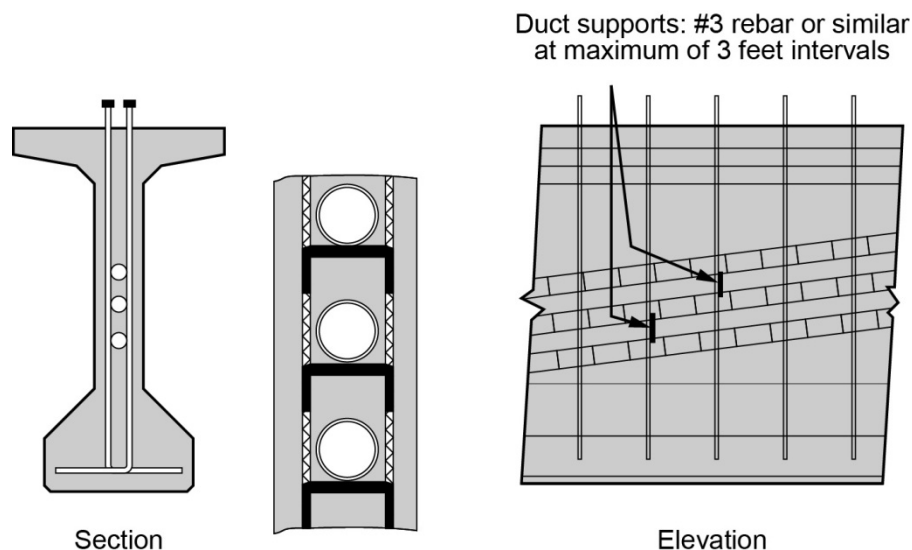


Figure 3.19 - Duct Supports in Post-Tensioned Precast I-Girders

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 polypropylene (PP) with purpose-made (sealed) connections; usually an outer plastic duct connector clips tightly around the duct.

Duct connections are now specified in accordance with the level of protection to be afforded the post-tensioning tendon. Refer to Section 3 of "Guide Specifications for Grouted Post-Tensioning", PTI/ASBI M50.3-12 for connections types permitted. Regardless of the connections type, it is important to make sure that supports do not fail and connections do not separate during casting (Figure 3.20).

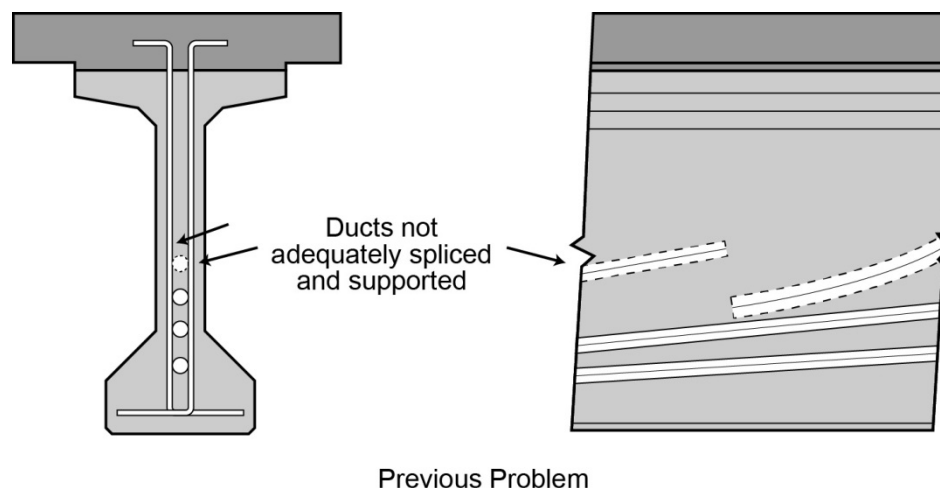


Figure 3.20 - A Possible Result of Poorly Supported and Connected Ducts

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, free water in ducts at the beginning of grouting, 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 3.21).

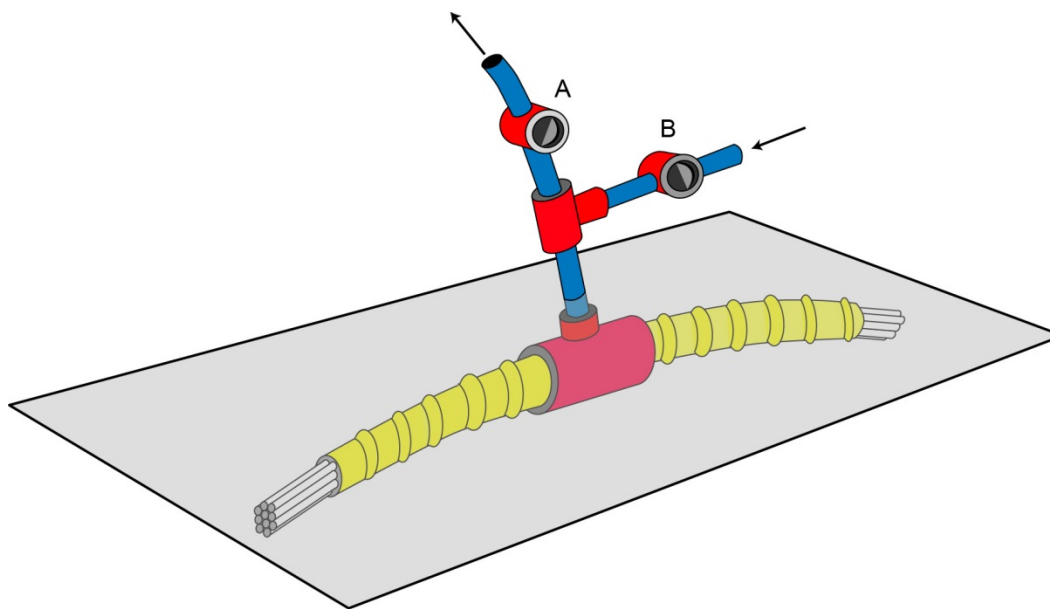


Figure 3.21 - Connections for Secondary, Vacuum Grouting Operations

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. 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 3.22), can make it difficult or impossible to install a tendon.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

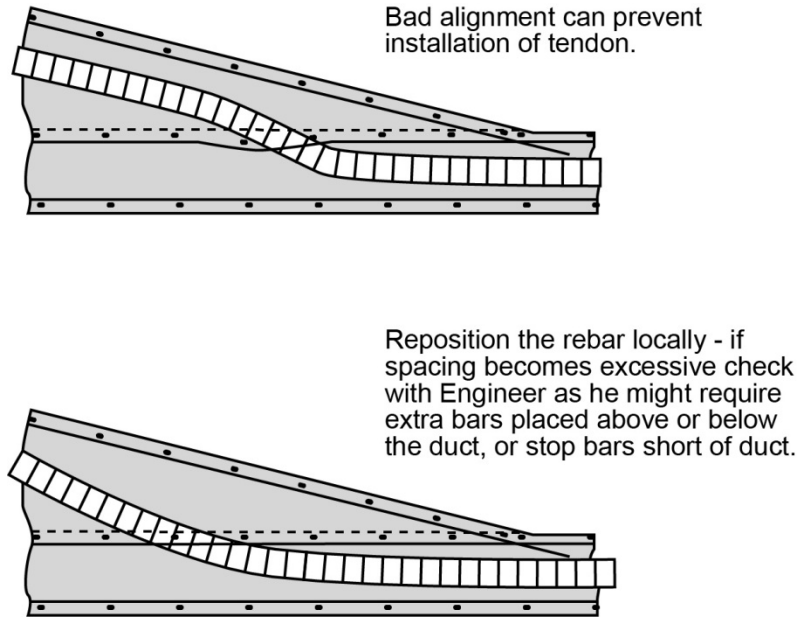


Figure 3.22 - Excess Wobble Due to Rebar and Duct Conflict

Concrete pressure itself is readily sustained by circular ducts. Flat 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 3.23). It is recommended that oval or circular ducts be used in webs and that sufficient space be provided for concrete to flow between ducts.

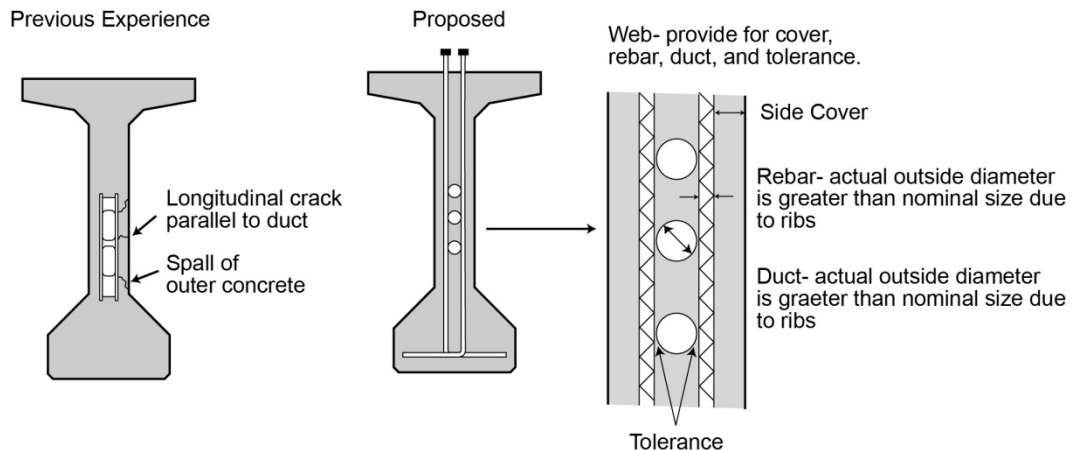


Figure 3.23 - Duct Size in Post-Tensioned I-Girders

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 3.24 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 helped solve this problem. Rather than try to fill the bottom slab completely from the webs, some concrete was first poured directly in the bottom slab (Step 1 in Figure 3.24). Next, concrete is placed in the bottom of the webs (Step 2 and 3). This concrete is worked together with the concrete poured in Step 1, with minimum lateral movement of the concrete. Once the bottom slab and bottom of the webs are poured and consolidated, the remaining web concrete is poured (Steps 5 and 6). Finally, the top slab is poured in Steps 6 through 10.

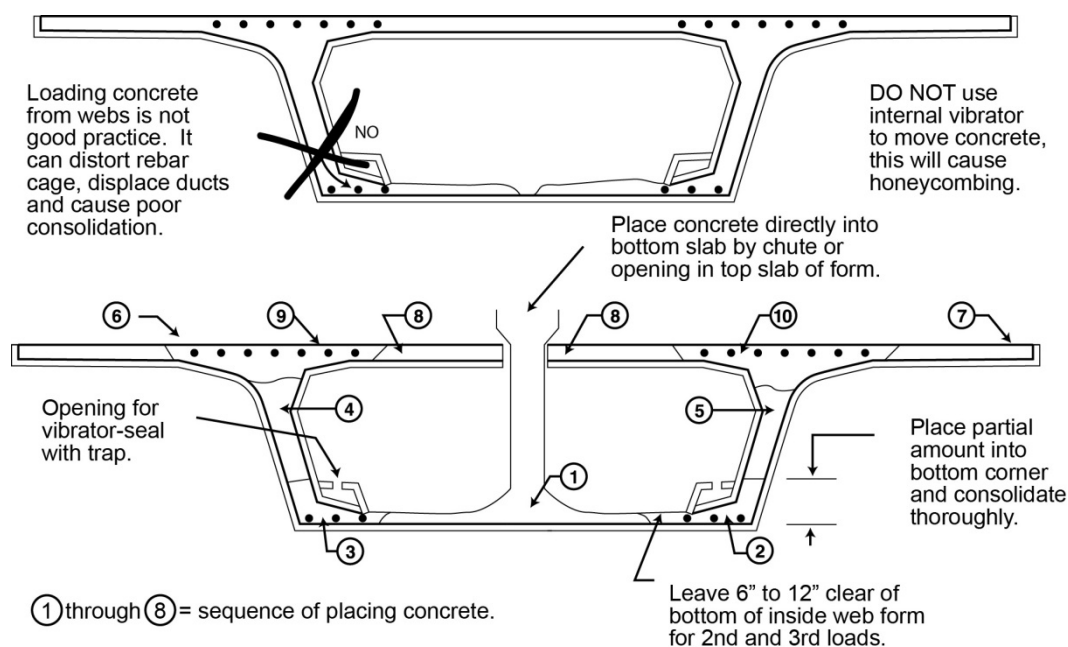


Figure 3.24 - Placing Concrete in Box Segments

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 3.25).

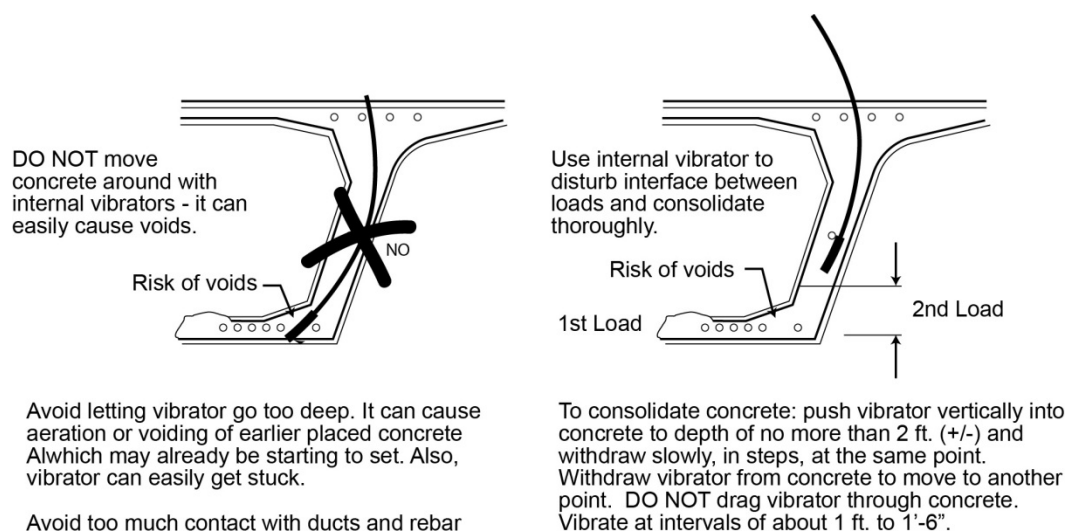


Figure 3.25 - Use of Internal Vibrators for Consolidation of Concrete

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 debris, 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 strand tendons are typically used for transverse tendons in the deck slabs of precast or cast-in-place segments, with up to five strands laid side-by-side in an oval duct draped to a very shallow profile.

Post-tensioning bar tendons are used for permanent applications, as shown in Chapter 1, Section 1.2.7. Temporary applications of bar tendons include the erection of precast segments, securing erection equipment such as gantries and form travelers during construction. 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% f_{pu} 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 (Section 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 (1/4in) 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 (1/4in) 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 or metal 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 3.26). Welding strands together should be performed in accordance with Section 11.2 of ASBI/PTI M50.

Post-tensioning tendons in flat ducts should be placed with the strands preinstalled to provide necessary rigidity and maintain alignment during concrete pouring. The strands of these tendons 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 3.26 - Steel wire sock for installing multi-strand tendon

3.5.4 Aggressive Environments

In aggressive environments, extreme care should be taken to ensure that water does not get into the ducts prior to installation of the prestressing steel. In the unlikely event that a duct may be contaminated with chlorides, flushing of the duct with water may be necessary to remove the chlorides before installing tendons. Only clean water should be used for flushing. The ducts should be well drained. All water should be removed before grouting. Flushing water should be blown out of the ducts before installing tendons, followed by swabbing the duct dry. All low point drains should be open during drying. Flushing should not be considered a standard practice and should only be done in emergency situations with the approval of the Engineer.

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; see “Specification for Grouting of Post-Tensioned Structures”, PTI M55.1-12.

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.

If circumstances preclude grouting within the designated time frame, additional corrosion protection measures may be warranted with the approval of the Engineer. These measures may include the use of water-soluble oils or vapor-phase inhibitors applied by the prestressing steel manufacturer or at the job site. However, care must be exercised because temporary corrosion products may reduce bond and some may also increase corrosion rates in certain environments. It is recommended that the manufacturer’s instructions be followed and other temporary corrosion protection products that have been tested for corrosion protection and bond reduction in representative PT conditions be used. In all cases, thorough and complete sealing of ducts to keep out moisture is the first line of defense. Water-soluble oils should not be removed by flushing prior to grouting.

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 on each side of the strand, with a wedge device for gripping and pulling the strand (Figure 3.27).



Figure 3.27 - Monostrand Jack

Mono-strand tendons are often used in buildings, where each tendon is a single strand in an extruded sheath. 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 3.28). It is extremely important that all strands are orientated properly to the holes in the jack. A "star plate" or "recessed plate" is used to ensure alignment. Push the "star plate" all the way up to the wedge plate to ensure alignment.

Prestressing jacks must be very accurate and should be carefully and frequently calibrated. 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.

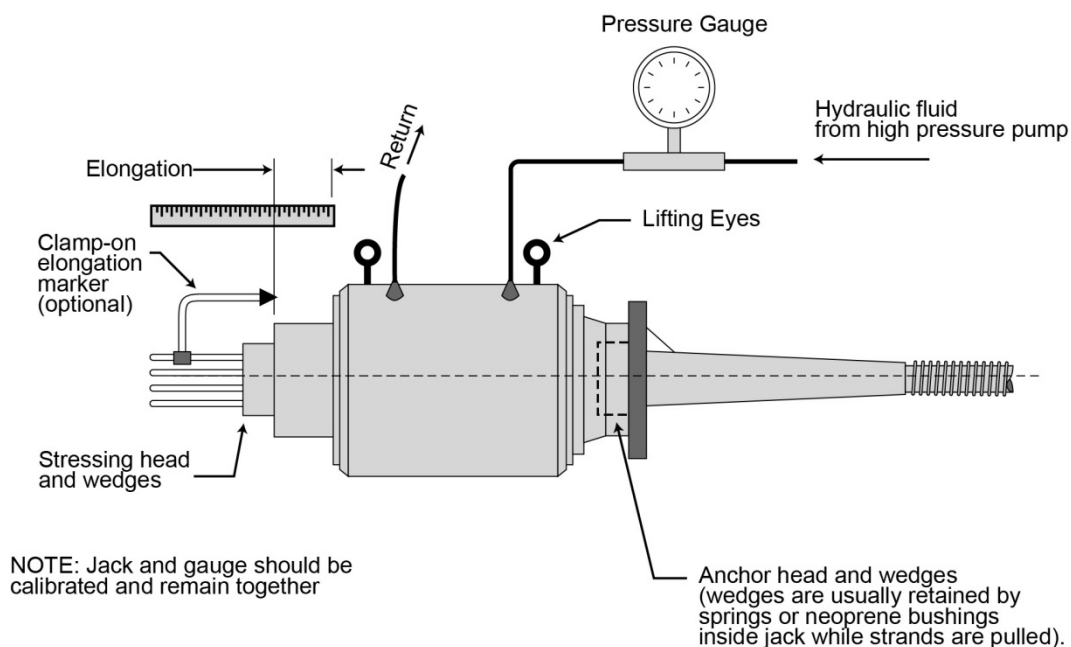


Figure 3.28 - Typical Multi-Strand, Center Hole, Stressing Jack

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 3.29). Most jacks have an enlarged nose to accommodate a bar-coupler.

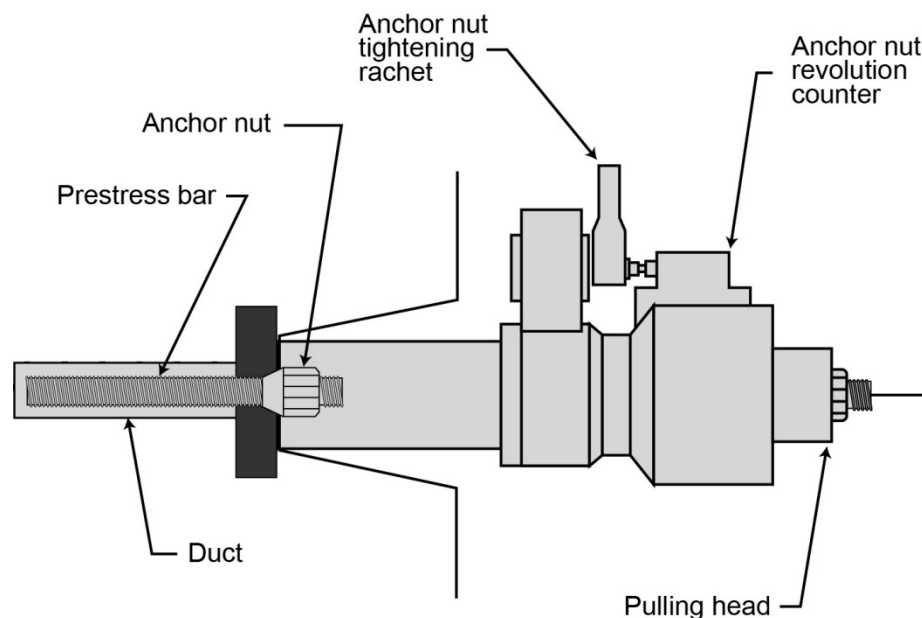


Figure 3.29 - Prestressing Bar Jack

Many 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. A chair and open-end wrench may be used in lieu of nose and ratchet for bar jacks. 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 in accordance with Section 12.5 of "Guide Specifications for Grouted Post-Tensioning", PTI/ASBI M50.3-12.

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, jacks and gauges 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 3.30 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.

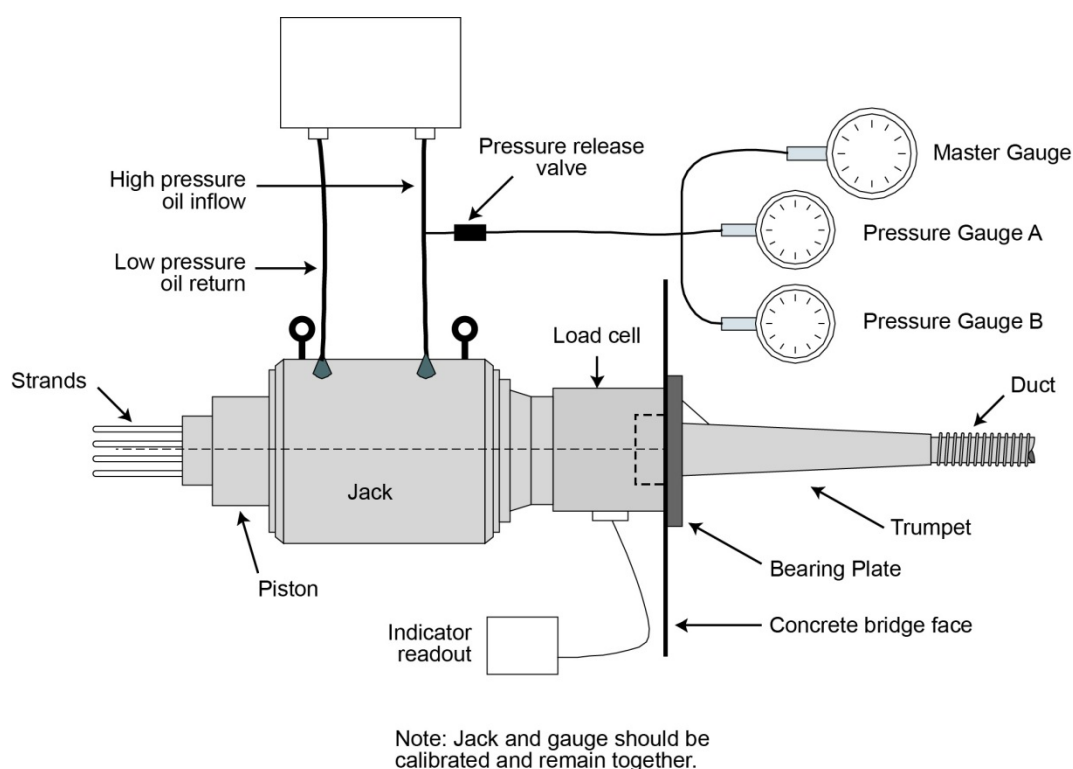


Figure 3.30 - Jack Calibration

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 3.31). 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.

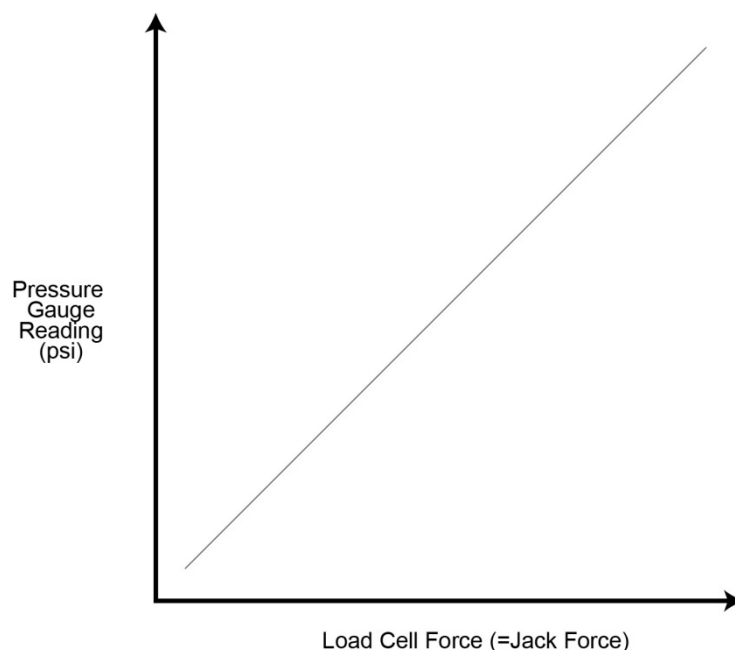


Figure 3.31 - Calibration Chart for Pressure Gauge and Jack Force

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 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. Single strand stressing is not suitable for multi-strand tendons with 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 tendons, and 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 anchor 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 than 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 3.32). 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.

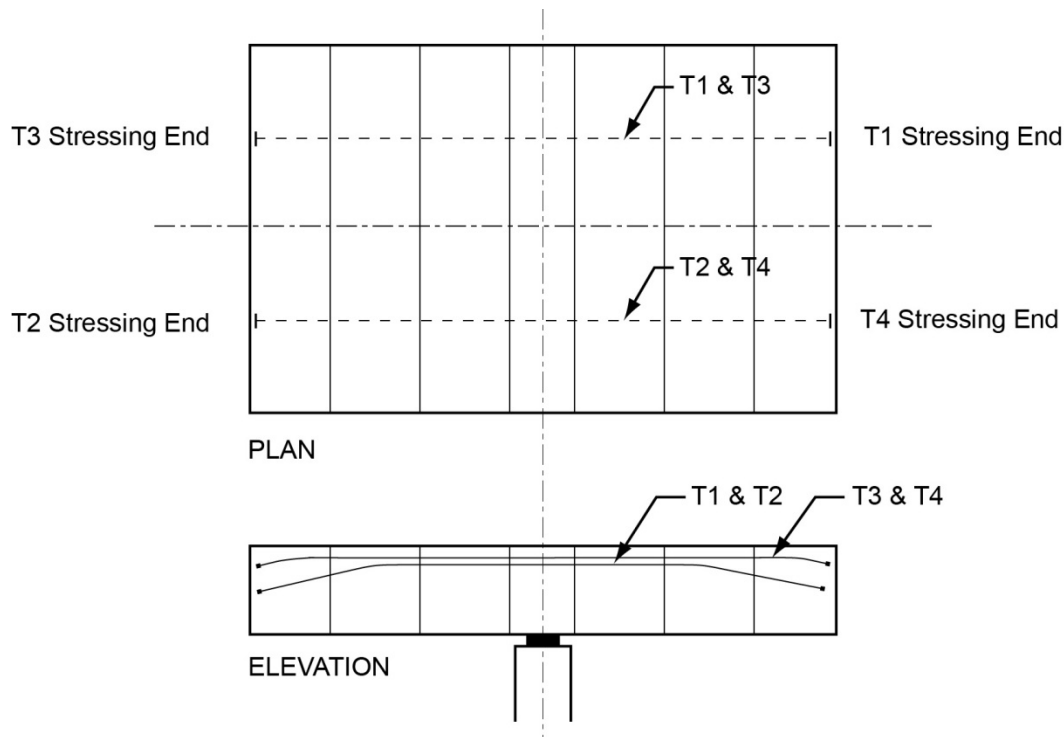


Figure 3.32 - Alternate End Stressing

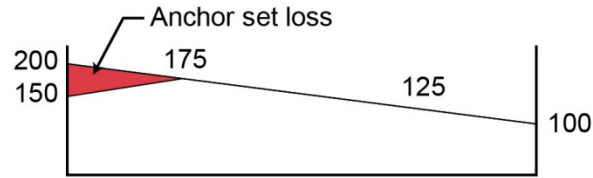
Alternate end stressing results in a more or less even distribution over the section. Since the tendons are stressed from one end only the forces at the live ends will be greater than the forces at the dead ends. Each individual tendon causes a non-symmetrical stress distribution.

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 3.33). Stressing from the second end should not be done if the calculated elongation is less than the length of the wedge grip. Re-gripping in a portion of the old grip length should be avoided.

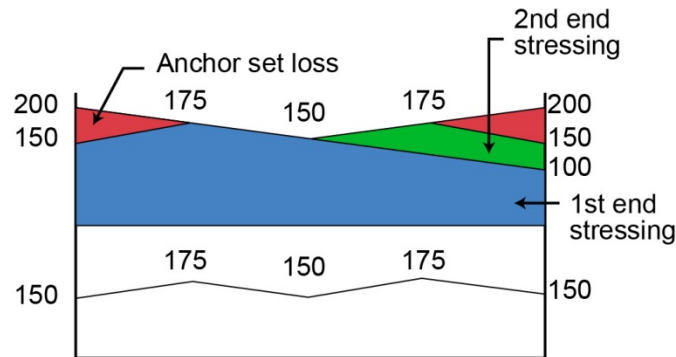
Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual



“One End Stressing” results in non-symmetrical stresses due to prestress



“Alternate End Stressing” results in symmetrical stresses due to prestress



“Two End Stressing” results in symmetrical stresses, and, in longer tendons, higher stress levels

Figure 3.33 - 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 3.29).

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 involves the application of high forces to the structure, which may represent a high risk to construction personnel if proper safety procedures are not followed. 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, as well as the minimum concrete strength required at stressing, 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, anchor 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.

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 anchor set 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. Anchor set 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 jack's pressure gauge.

For permanent PT bars, elongations may be checked as secondary verification of force. PT bars elongations, if required, may be measured from 0% P_{jack} , assuming bar was first cycled up to minimize any "slack", i.e. coupler or nut slop. Typically, bar elongations can be difficult to reconcile. In lieu of elongations as a secondary check, lift-offs may be performed for verification of force.

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 (" $\mu\theta$ ").
- Friction between the tendon and duct due to unanticipated wobble ("k").
- 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

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 anchor set is between 1/4 inch and 3/8 inch (Figure 3.34).

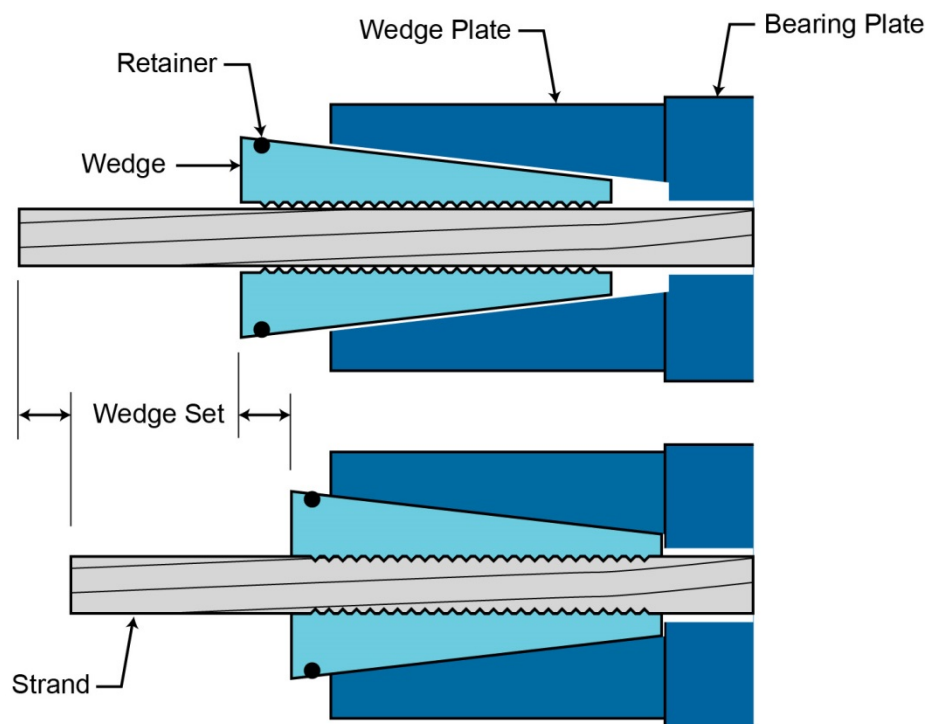


Figure 3.34 - Anchor Set or Wedge Set

Some jacks have devices that power-seat the wedges prior to releasing the force. In addition to the wedge seating, there is an elastic deformation of the wedge plate – it is relatively small compared to the wedge set. Together, these effects may be referred to as “anchor 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.

Anchor 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 best practice to make sure that intermediate re-gripping does not take place at a location that has already been gripped by wedges. Intermediate re-gripping can lead to strand slip or breakage.

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 Section 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 anchor 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 shown at the end of this Chapter.

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, and with the approval of the Owner's representative on site. 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 (1/2in to 3/4in) 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 or plasma cutter. Under no circumstances should flame cutting be used as the heat can soften the strands and wedges and lead to loss of strands.

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 through 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. Jack chairs are often required to obtain tendon lift-offs. The lift-off force determined is the tendon force at the anchorage after the seating loss of the original stressing.

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 if problems occur during the stressing operation. Refer to Section 12.11 of "Guide Specification for Grouted Post-Tensioning", PTI/ASBI M50.3-12 for the information that should be included in the stressing records.

A sample stressing report is provided at the end of this Chapter.

3.10 Stressing Problems and Solutions

Several problems can be encountered during stressing operations. The following Sections address 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. Dirty or rusty wedges or rusty wedge plate holes are the most frequent cause of wedge slippage. The dirty or rusty surfaces prevent 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 informed 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 informed.

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 may need 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 of relatively little concern. For instance, when one wire breaks only $1/7^{\text{th}}$ 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.

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. Persistent wire breakage should be investigated and action taken to change procedures or equipment to avoid or significantly lessen the problem.

Refer to Section 12.8 of "Guide Specifications for Grouted Post-Tensioning," PTI/ASBI M50.3-12 for limits with regard to broken wires.

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. Strand that is not used within standard shelf life may lose some of the relaxation properties and give excessive elongations.

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 similar tendons with appropriate water soluble oil or graphite powder. This can reduce friction and result in better elongations.

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. Also, the jack calibration should be checked against the master gauge.

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 Additional Tendons

If none of the above lead to a satisfactory solution, it may be necessary to introduce or install additional tendons through provisions made on the plans or shop drawings.

In all cases above, if addition of similar tendons are to be constructed in portions of the bridge yet to be poured, review and improve details for securing tendons during the pours. Refer to "Rational Application of the Elongation Tolerance for Post-Tensioning Tendons", by Freyermuth for additional information (See Appendix C).

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

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

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.

STRESSING REPORT				Page 1 of 2			
Project name:				Job No.			
Contractor:				Stressing Sub-Contractor:			
Tendon Location:				Tendon Number:			
Tendon Size:				PT Steel Supplier:			
Assumed for Calculations				Actual Values Delivered per Pack or Reel of Strand			
Number of Strands, Ns:				Strands from Reel No:			
Assumed Strand Area, As:				Number of Strands per Reel, Nr:			
Assumed Modulus, Es:				Actual Strand Area per Reel, Ar:			
Product, Ns*As*Es =				Actual Modulus per Reel, Er:			
				Product, Nr*Ar*Er =			
				Sum of Products: Sum(Nr*Ar*Er) =			
Adjusted Elongation Expected = [Nr*Ar*Er / (Sum(Nr*Ar*Er))]							
First Stage Stressing from End A				Second Stage Stressing from End B			
		Jack Force (kip)	Gauge (psi)			Jack Force (kip)	Gauge (psi)
Required force before wedge set:				Required force before wedge set:			
Theoretical elongation, ΔA, (ins) =				Anticipated pick-up force:			
		Theo ΔA+ΔB =				Theoretical elongation, ΔB, (ins) =	
Adjusted elongation, ΔA, (ins) =		Adj ΔA+ΔB =		Adjusted elongation, ΔB, (ins) =			
Expected Wedge Set, End A, Wa:				Expected Final Wedge Set, End B, Wb:			
		Jack	Gauge			Jack	Gauge
Equipment Identifiers End A:				Equipment Identifiers End B:			
Stressing Mode:							
One End only:		Both A then B:		Both Simultaneous (A and B with 2 sets of equipment):			
Target Gauge Pressures and Elongations							
End A				End B			
	Pressure	Elongation per increment	Wedge Set	Pressure	Elongation	Wedge Set	
Elong before set at A = ΔA = (Sum) =				Elong before set at B = ΔB = (Sum) =			
Net Elong after wedge set at A =				Net at B after set =			
Overall anticipated elongation =							

Figure 3.35 - Example Stressing Record Page 1 of 2

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

STRESSING REPORT							Page 2 of 2	
Elongation Measurement:								
End A			End B				Increment of Elong per 20% of Load	Average per 20%
First Stage Stressing	Pressure	Elongation	Wedge Set at A, Wa	Pressure	Elongation	Wedge Set at B, Wb		
Initial 20%								
40%								
60%								
80%								I
Final 100% at A								I
Second Stage Stressing								I
Pick-up at B								I
Final 100% at B								V
Elongation at A from 20 to 100% =								V
Add for initial 20% load =								
Elongation at A before set =				Elongation at B before set =				
Total Elongation before set =								
Total Wedge Set =								
Deduct for elongation inside jack =								
Final Elongation =								
Expected Elongation =				Ratio of (Final / Expected) =		%		< 7% O.K.
Approved: _____				Not Approved: _____				(AASHTO LRFD Construction or Project Specs.)
Observations: <i>No popping noises of broken wires O.K. Over elongation is within tolerance, O.K.</i>								
Signed - Stressing Foreman: _____						Date: _____		
Signed - Inspector: _____						Date: _____		

Figure 3.36 - Example Stressing Record Page 2 of 2

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 of 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 of 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 and the vertical distance (head) between the grout pump and the inlet.

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. Testing should be in accordance with Section 13.1 of "Guide Specification for Grouted Post-Tensioning", PTI/ASBI M50.3-12.

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.

Leaks should be sealed in an appropriate manner – such as tightening or re-sealing 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, Water Measurement

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 required 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.

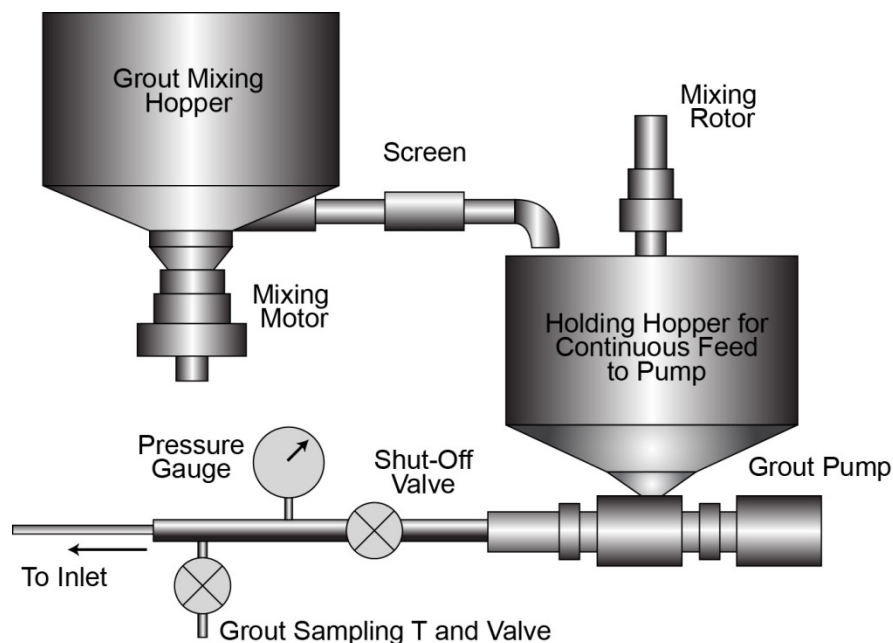


Figure 4.1 - Grout Mixing and Pumping Equipment

The grouting equipment shall use a gravity feed to the pump inlet from the agitator attached to and directly over it.

Type B and C grouts shall be mixed using a high speed mixer. High speed mixers shall have a storage hopper incorporated between the mixer and pump. The storage hopper shall be fitted with an agitator to keep the grout moving continuously before it is pumped into the duct.

The storage hopper must be kept at least partially full at all times during the pumping operation to prevent air from being drawn into the PT duct.

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) or more than 3m (10ft) apart in elevation, the system should have a gauge at the pump and another at the inlet. Best practice would be to always use two pressure gauges.

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 ($\frac{3}{4}$ 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.

Water Measurement

Accurate measurement of water is necessary for the production of high quality grouts. Measurement of water by water meter or calibrated buckets should be provided.

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 (Modified ASTM C939).
- American Petroleum Institute (API) Mud-Balance for density tests.
- 50mm (2 inch) molds for making strength test cubes. (Some agencies prefer using 3" diameter cylinders for cube tests).
- Cylinders and strand sample for Wick Induced Bleed Test (Modified ASTM C940).
- For thixotropic grout - Schupack Pressure Grout Test kit.

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).

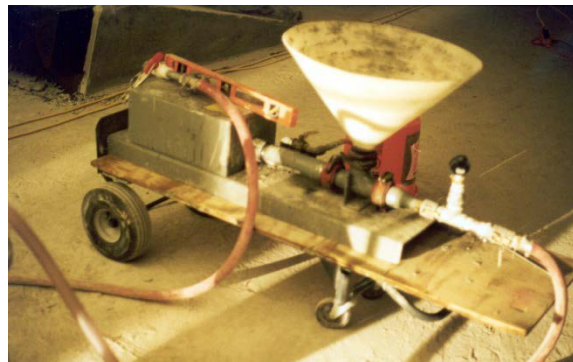
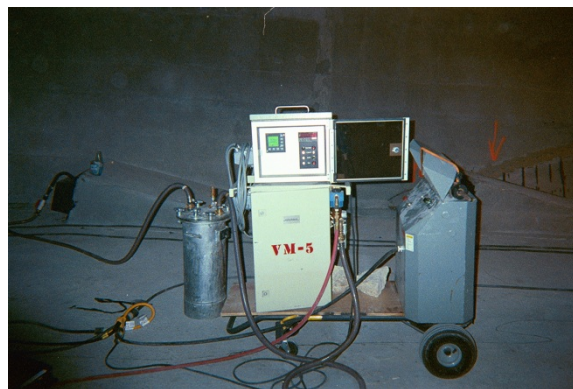


Figure 4.2 - Vacuum Grouting Equipment, Digital Volumeter (up (upper left), Void Volume Measurement (upper right), Grout Pump (lower left), Vacuum Grout injection (lower right)

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.

In the event grouting operations are interrupted, leaving partially filled tendons, vacuum grouting equipment should be available to fill the remaining unfilled portions of the duct.

4.3.2.5 Clean Grouting Equipment

All grouting equipment should be thoroughly cleaned and dried after grouting.

4.3.3 Batching and Mixing

Pre-qualified, pre-bagged grouts should be mixed in accordance with manufacturer recommendations. Grouts to be blended on site should be in accordance to the project approved grout mix design. 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 amount of time that the water is mixed/recirculated before adding grout should be minimized to help keep temperatures down. 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 3 minutes for a high-speed shear mixer.

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

- For a vane (paddle) mixer: all the water, about 2/3 cementitious material, the admixture, the remaining cementitious material.
- For a high-speed shear (colloidal) mixer: water, admixture, and 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 be performed on the mix for that day or a Schupack Pressure Bleed Test.

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 Section 4.4.6.2 of "Specification for Grouting of Post-Tensioned Structures", PTI M55.1-12.

4.3.4.2 Prior to Injection at Inlet

For non-thixotropic and 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 in accordance with the manufacturer's requirements. The modified ASTM C939 testing will set the target efflux time for the project. After allowing the grout to stand for 30 minutes without agitation and then remixing for 30 seconds, the efflux time should be within +/- 5 seconds of the target efflux established by testing.

The wet density of the discharged grout should be checked using the ANSI/API Mud Balance Test. The measured density should fall within acceptable values.

4.3.4.3 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 C939 flow cone test (Figure 2.13).

The efflux time should be within the range established by testing. If the efflux time is too short, then more grout should be discharged and tested again. This should be repeated until the grout has an acceptable uniform consistency and is within the range established by testing.

The wet density of the discharged grout should be checked using the ANSI/API Mud Balance Test. The measured density should fall within acceptable values.

4.3.4.4 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 C939 flow cone test (Figure 2.13). The efflux time should be within +/- 5 seconds of the target efflux time established by testing.

The wet density of the discharged grout should be checked using the ANSI/API Mud Balance Test. The measured density should fall within acceptable values. [Note: This may be the 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 (Section 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

Pumping should be done at the lowest pressure possible that will fill the tendon in a reasonable amount of time but should not exceed 0.52 MPa (75 psi) at the inlet. Pumping pressures should not exceed 1MPa (145 psi).

Although higher pressures than this might be sustained by internal ducts of plastic 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 5m (16 feet) to 15m (50 feet) 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 Incomplete Grouting

When complete grouting by the above methods cannot be achieved, then grouting should proceed to the last vent where grout was observed or the grouting operation should be terminated. Grouting from the far end of the duct should not be done once it has started from the original end.

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). Other NDE method for void detection, such as infrared thermography, echo impact, and sounding (external tendons) may be used where appropriate.

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. Stand pipes should be used to assure complete filling of the tendon.

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. Inspection should identify any voids and the presence of soft grout.

All inlets and outlets should be inspected to ensure complete filling with grout. Figure 5.4 and 5.5 shows typical inlet and outlet arrangements that may be accessed and visually inspected and probed. 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. The grout inlet and outlet caps should be removed and the inlet and outlet probed for voids. If a void is suspected, 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:

- For bridges with fewer than 20 tendons, 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 does 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 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 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.

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 epoxy manufacturer.

4.3.11 Protection of Post-Tensioning Anchorages

After grouting, all post-tensioning anchorages should be properly prepared and protected as necessary. Anchorages should be protected in accordance with "Guide Specifications for Grouted Post-Tensioning", PTI/ASBI 50.3-12.

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), lot or batch number
- 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
- Number of days from strand installation to grouting.

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 Incomplete Grouting

In the event grouting operations are interrupted, leaving partially filled tendons, vacuum grouting equipment should be available to fill the remaining unfilled portions of the duct. Flushing of tendons is not a recommended practice, but a last resort to be performed under the direction of the Engineer.

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. Abandon the batch and begin again with new material.

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, D, E, G, B.

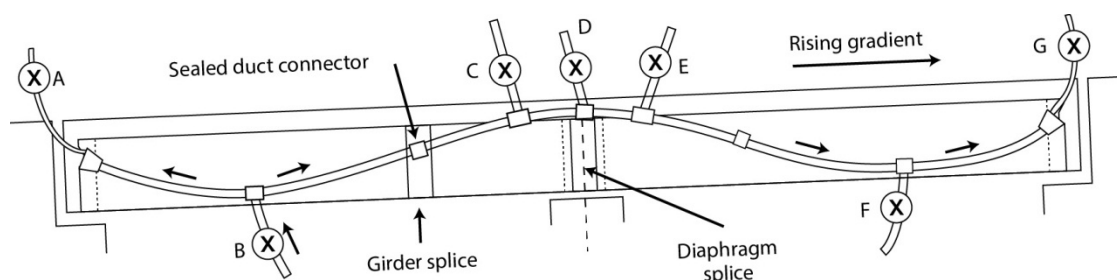


Figure 4.3 - Grouting Details for a 2-Span Spliced Girder Duct System

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.

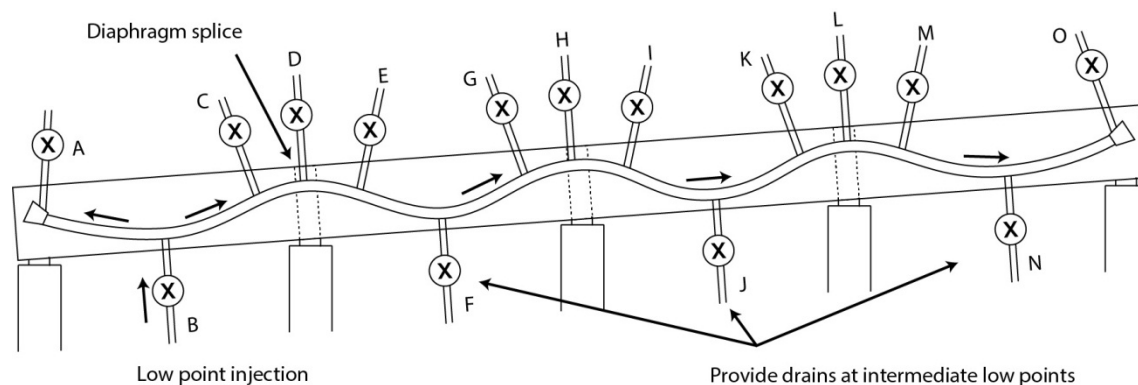


Figure 4.4 - Grouting Details for a 4-Span Spliced Girder Duct System

- 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.

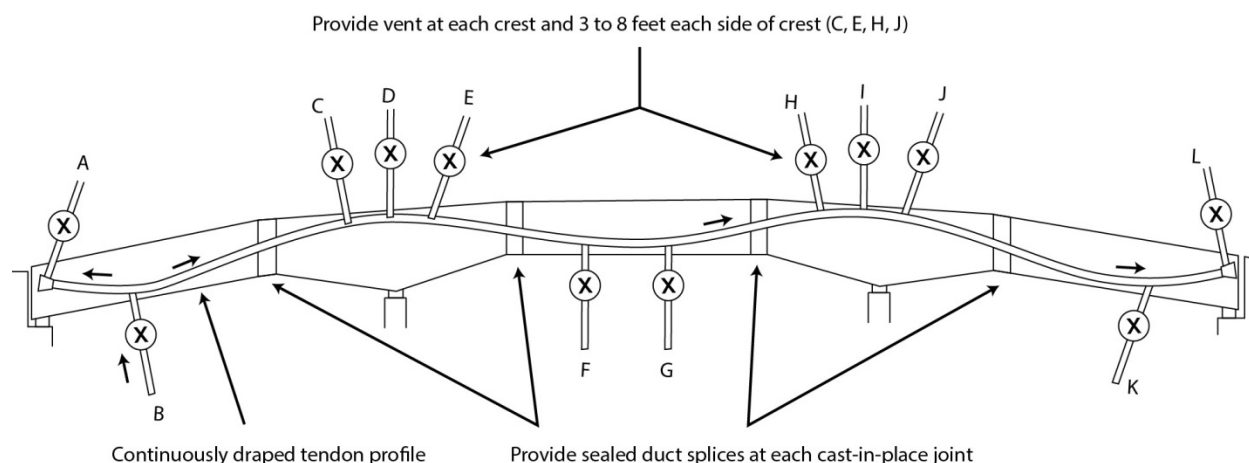


Figure 4.5 - Grouting Details for a 3-Span, Drop-in and Spliced Girder Duct System

- 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.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

- 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).

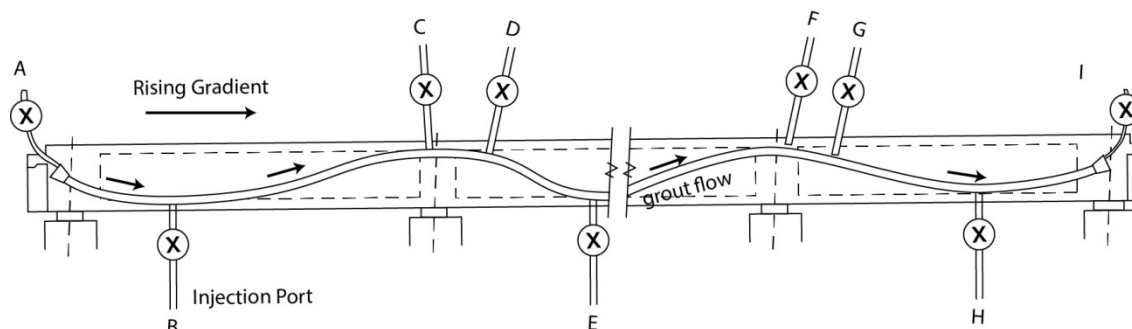


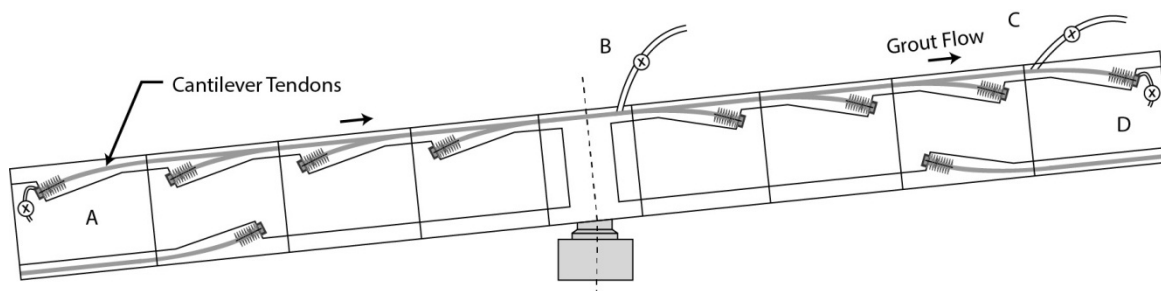
Figure 4.6 - Grouting Details for Cellular Box Girder, Voided, or Solid Slab Duct System

- 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 apply. 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).



- Injection port at top of anchor (A)
- Intermediate vent (B)
- High point vent (C)
- Outlet vent at top of anchor (D)

Figure 4.7 - Grouting of Cantilever Tendons (Top Continuity Tendons Similar)

- 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.) Note: Could grout from A if less than 20" difference in heights of other inlets/outlets.
- 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 50m (150 ft). Also add a vent if the tendon profile rises more than 20".
- Provide another injection port (D) if tendon profile is more than 0.5m (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.

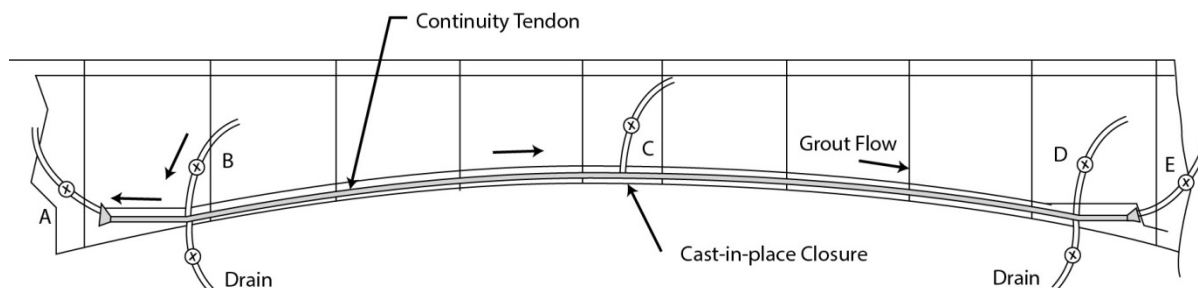


Figure 4.8 - Grouting Bottom Continuity Tendons in Variable Depth Box Girders

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.

Access to an injection port at the low point (B) may be difficult. When this is the case, the tendon may be injected from the lower of the tendon ends (A or E). The rate of grouting should be monitored carefully, as not to allow the grout to cavitate as it flows from the injection port (A or E) to the low point (B).

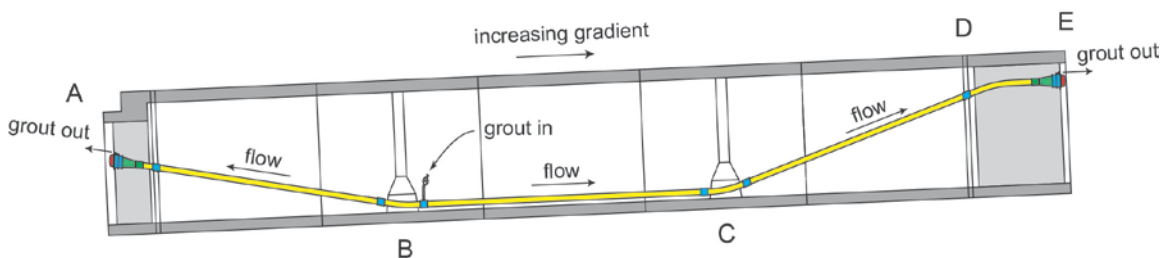


Figure 4.9 - Grouting details for end span, external tendon

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.

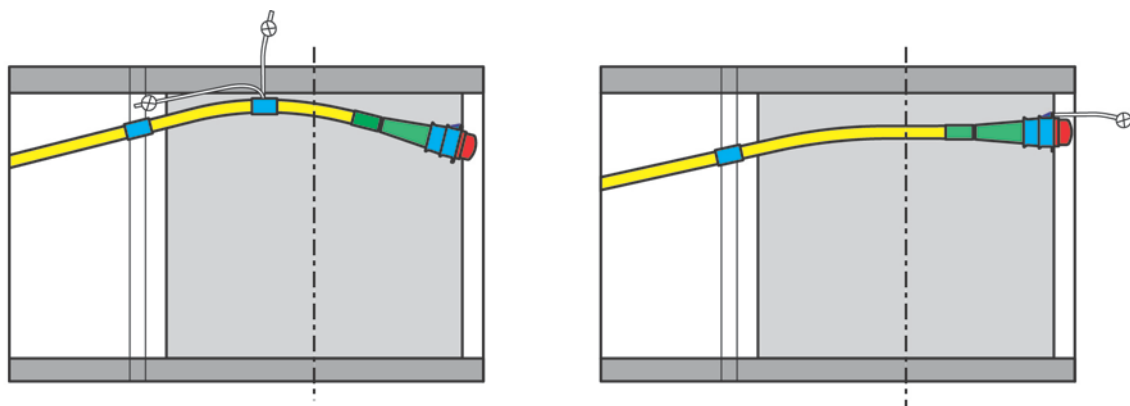


Figure 4.10 - Grouting vent locations at pier segments in span-by-span bridges

4.5.8 Example 8: Inlet and Outlet Connections to Bottom External Tendon (Figure 4.11)

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.

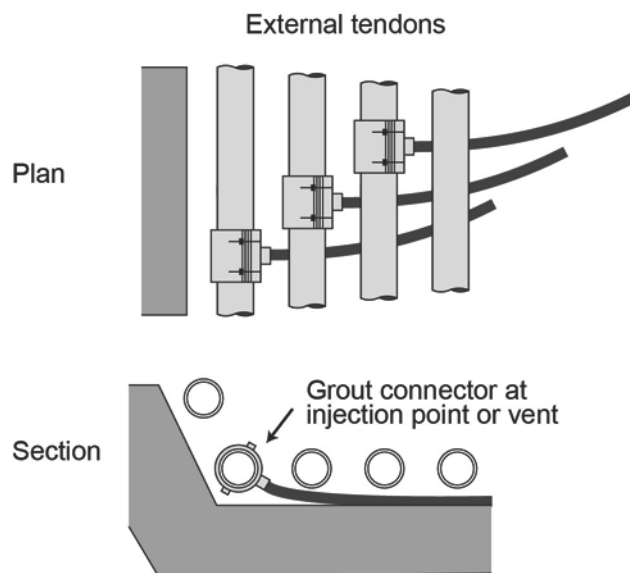


Figure 4.11 - Possible Grout and Drainage Connections for Bottom External Tendons

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 where the geometry of the tendon warrants.
- Inject from one end of cap.
- First close vent at opposite end of cap after evacuating grout.
- Vent grout at high point outlet.
- Close high point vent, then close inlet.

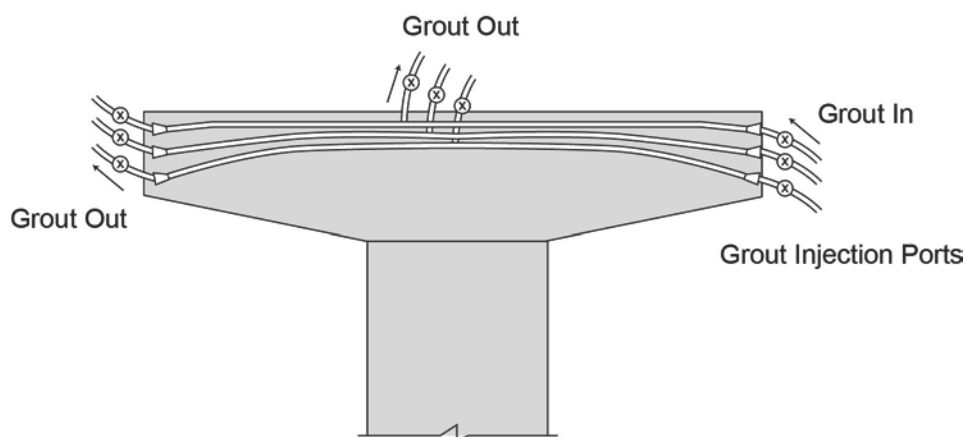


Figure 4.12 - Grouting Details for Lateral Tendons in Hammerhead Pier Cap

4.5.10 Example 10: Vertical Post-Tensioning in Pier (Figure 4.13)

Vertical post-tensioning tendons in a pier are illustrated in Figure 4.13. The legs of the tendons should be grouted simultaneously. 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.

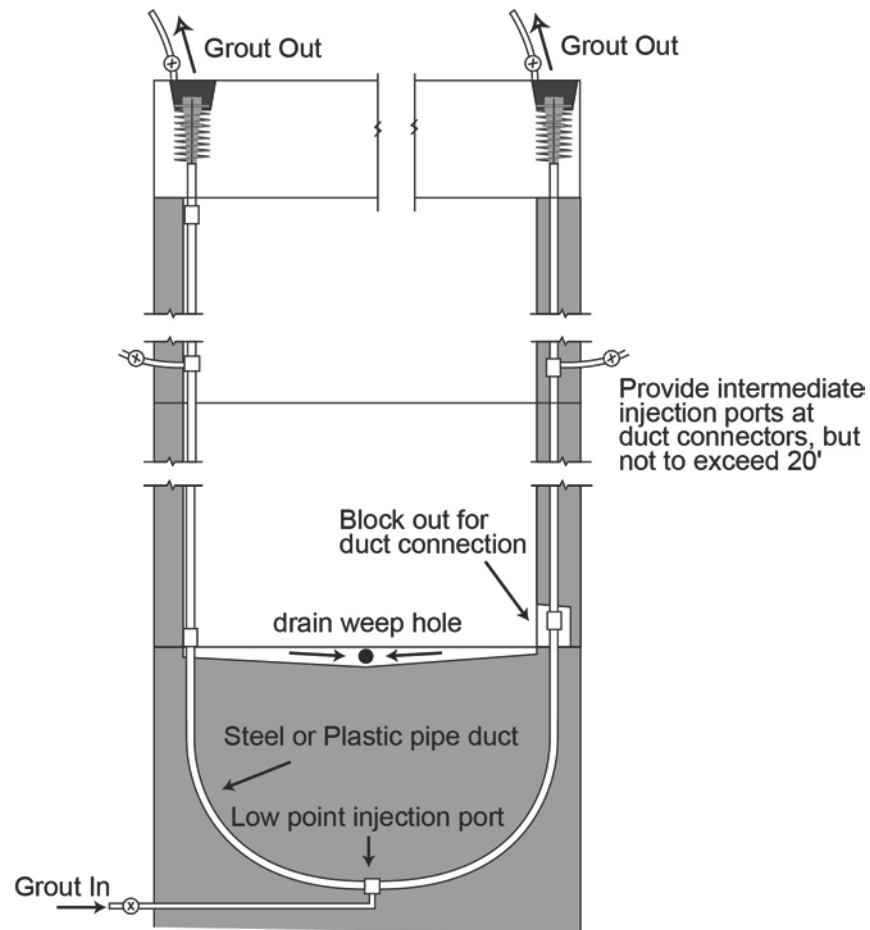


Figure 4.13 - Grouting Details for Vertical Tendons in Piers

4.5.11 Example 11: Cantilever C-Pier (Figure 4.14)

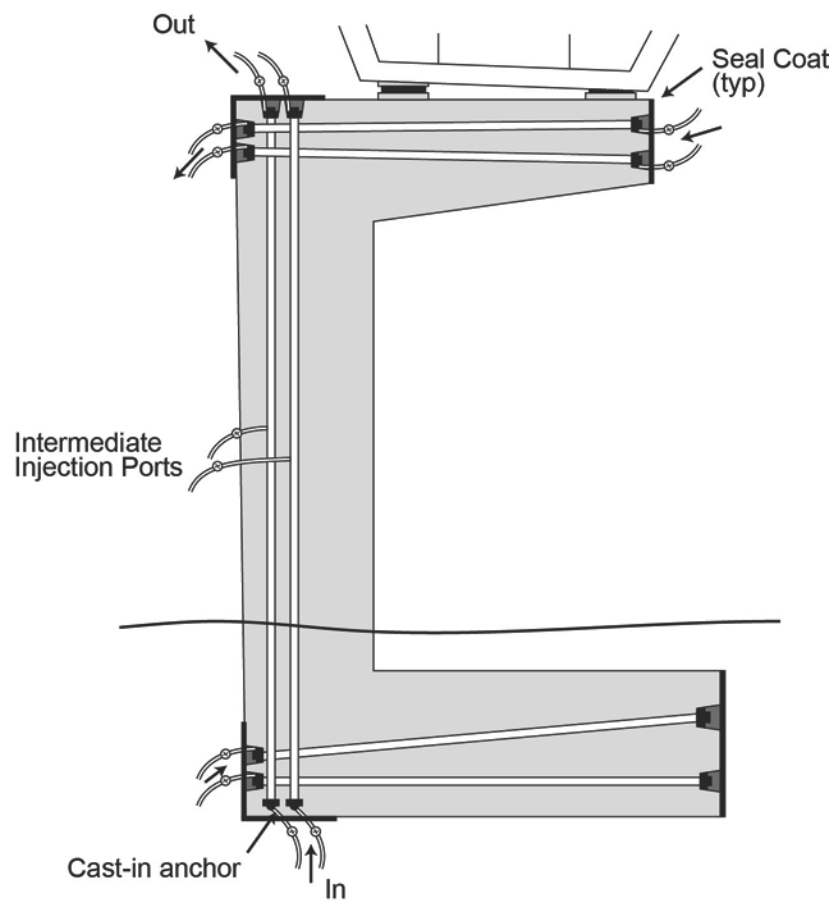


Figure 4.14 - Grouting Details and Anchor Protection for Vertical and Lateral Tendons in C-Pier

Chapter 5 – Corrosion Protection of Post-Tensioning Tendons

5.1 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.

5.1.1 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. Today, duct couplers are required for all internal tendons as they cross joints between segments.

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 block-outs.
- 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. Early precast segmental designs did not use any epoxy at all or in some cases only on one face. (Texas was the 1st state to require epoxy on both faces).

- Grouting procedures created voids due to insufficient filling and use of grout mixes susceptible to bleed water and accumulation of entrapped air. Expanding admixtures were used to try to make sure the ducts were filled with grout - these did not work as intended and large voids and split ducts were a common result.
- Although galvanized ducts offered sacrificial 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.

5.1.2 Corrosion Protection of Post-Tensioning Tendons

Corrosion protection of post-tensioning systems can be provided by a number of possible levels according to the system details. Figure 5.1 shows six possible levels of protection available for typical post-tensioning tendons in bridge structures.

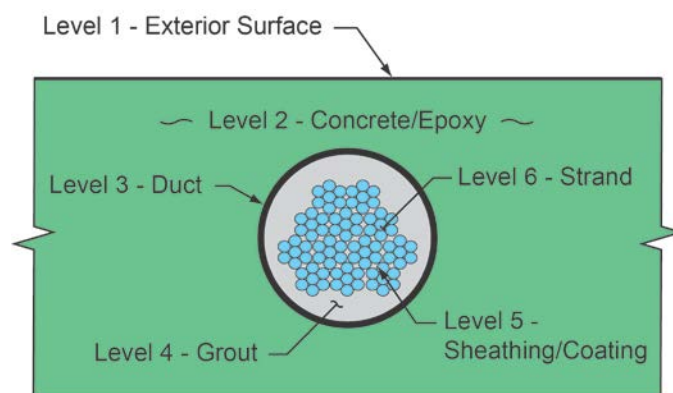


Figure 5.1 – Levels of Protection for Corrosion Protection

The six possible levels of protection shown in Figure 5.1 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 are made continuous through the use of duct couplers.
- 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.
- 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. 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.

5.1.3 Post-Tensioning System Tendon Protection Levels

The PTI Committee M-50/ASBI Joint Task Group has produced standardized Tendon Protection Levels (PL) for Post-Tensioning Systems in Section 3 of "Guide Specifications for Grouted Post-Tensioning", PTI/ASBI M50.3-12. Four protection levels are defined: PL-1A, PL-1B, PL-2, and PL-3. Corrosion protection requirements increase with an increasing Tendon Protection Level designation. The protection levels provided in PTI/ASBI M50.3-12 are:

- PL1A – Duct with filling material providing durable corrosion protection.
- PL1B – PL1A plus engineered grout and permanent grout caps.
- PL2 – PL1B plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak-tight barrier.
- PL3 – PL2 plus electrical isolation of tendon or encapsulation to be monitorable or inspectable at any time.

The engineer shall determine the tendon PL required for the project based upon the aggressivity of the environment, the exposure of the structure or element, and the protection provided by the structure and shall identify the tendon PL in the Contract Documents. Refer to "Selecting Post-Tensioning Protection Levels" (Krauser) for guidance for the selection of Tendon Protection Level for specific post-tensioning applications.

5.2 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.

5.2.1 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 low permeability concrete. Also, coatings or sealants can offer further protection.

5.2.2 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 be abraded and suffer local damage as strands rub and bear against the duct wall during installation and stressing. However, this should not normally be a problem because most specifications require ducts to have a minimum wall thickness and that the ducts be tested for wear resistance.

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.

5.2.3 Grout

Cement grout is chemically alkaline and provides a passive environment around strands. In internal tendons, concrete cover is 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.

5.2.4 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.

5.3 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:

5.3.1 Internal Tendons

Internal tendons are protected by grout, duct and concrete cover (Figure 5.2):

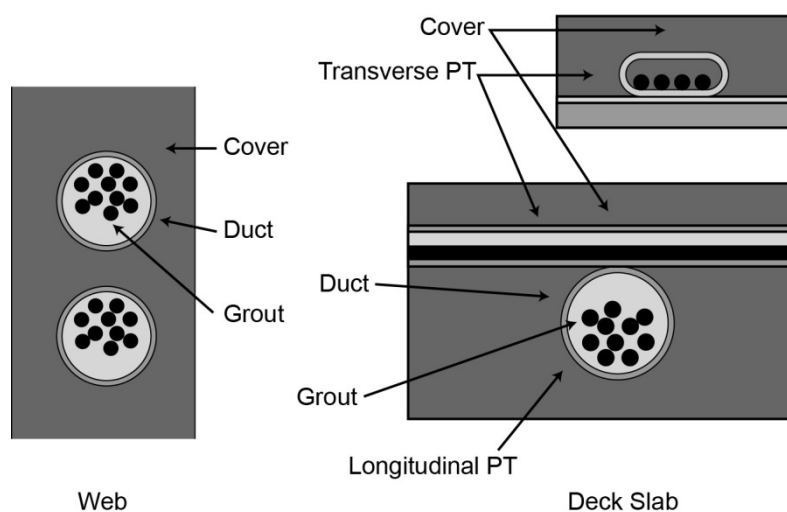


Figure 5.2 – Levels of Protection to Internal Tendons

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).

For precast segmental bridges, duct continuity is assured through the use of duct couplers. Duct couplers should be provided in accordance with Section 4.3.8 of “Guide Specifications for Grouted Post-Tensioning”, PTI/ASBI M50.3-12.

5.3.2 External Tendons

External Tendons are protected by grout, duct and the surrounding structure which should be “watertight” and well drained (Figure 5.3). 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.

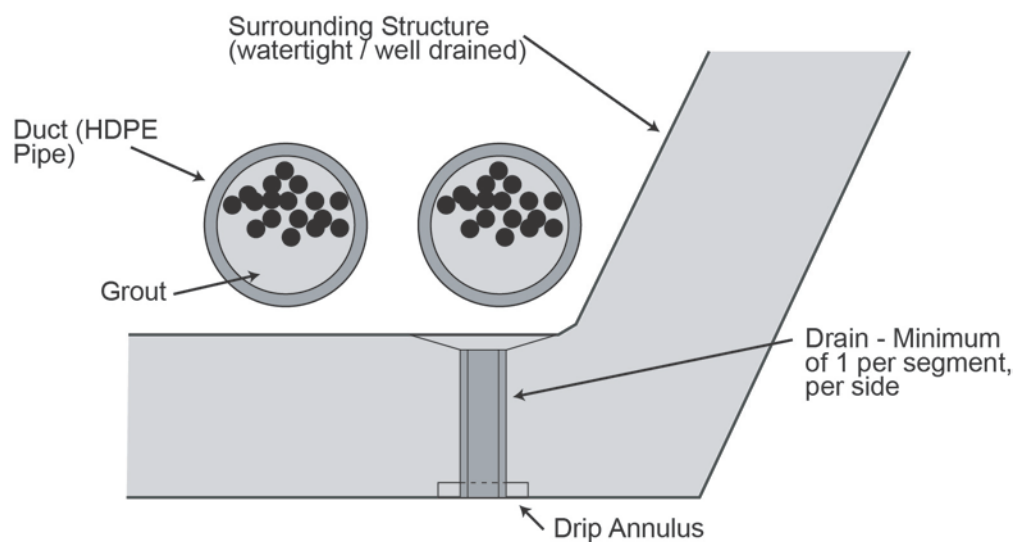


Figure 5.3 – Levels of Protection to External Tendons

5.4 Sealing Intermediate Inlets and Outlets

5.4.1 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 5.4).

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

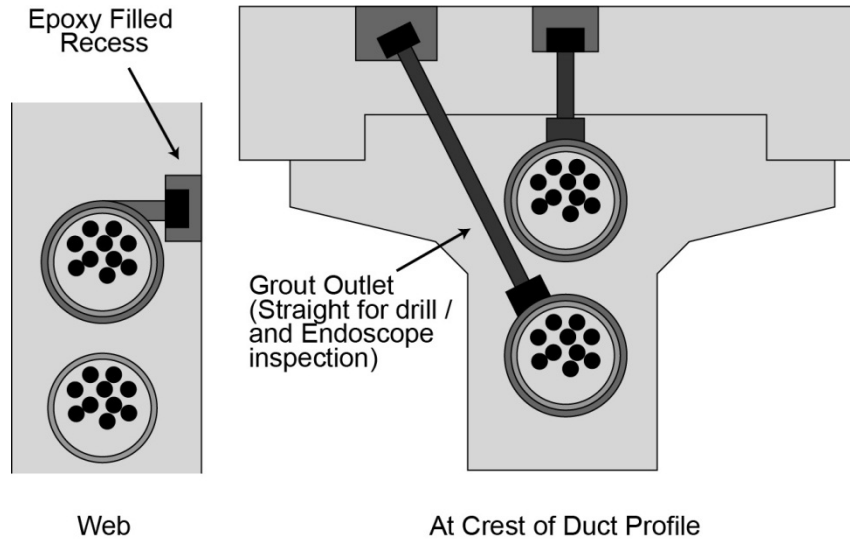


Figure 5.4 – Sealing of Inlets and Outlets along Internal Tendons

5.4.2 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 5.5). The outlet pipe should be straight to facilitate drilling and inspection with an endoscope, if necessary, to ensure that grout completely fills the tendon.

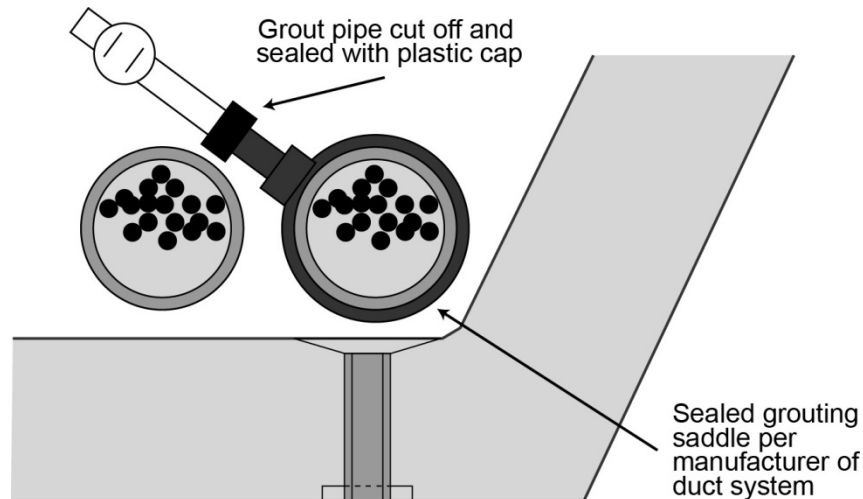


Figure 5.5 – Sealing of Inlets and Outlets along External Tendons

5.5 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 block-outs 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.

5.5.1 Anchorage Protection Considerations

Measures should be taken to properly protect anchorages. Minimum corrosion protection for anchorages should be in accordance with the protection levels specified in Section 3 of “Guide Specifications for Grouted Post-Tensioning”, PTI/ASBI M50.3-12.

Often further consideration need to be taken with regard to corrosion protection of anchorages. In this case, the following features should be considered.

- Grout – a fully filled tendon, anchor and grout cap.
- Permanent grout cap.
- 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.

5.5.2 Permanent Grout Caps

Permanent grout caps of an inert material (an approved plastic, galvanized metal, or stainless steel) 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.

5.5.3 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.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

- 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 5.6) 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.)

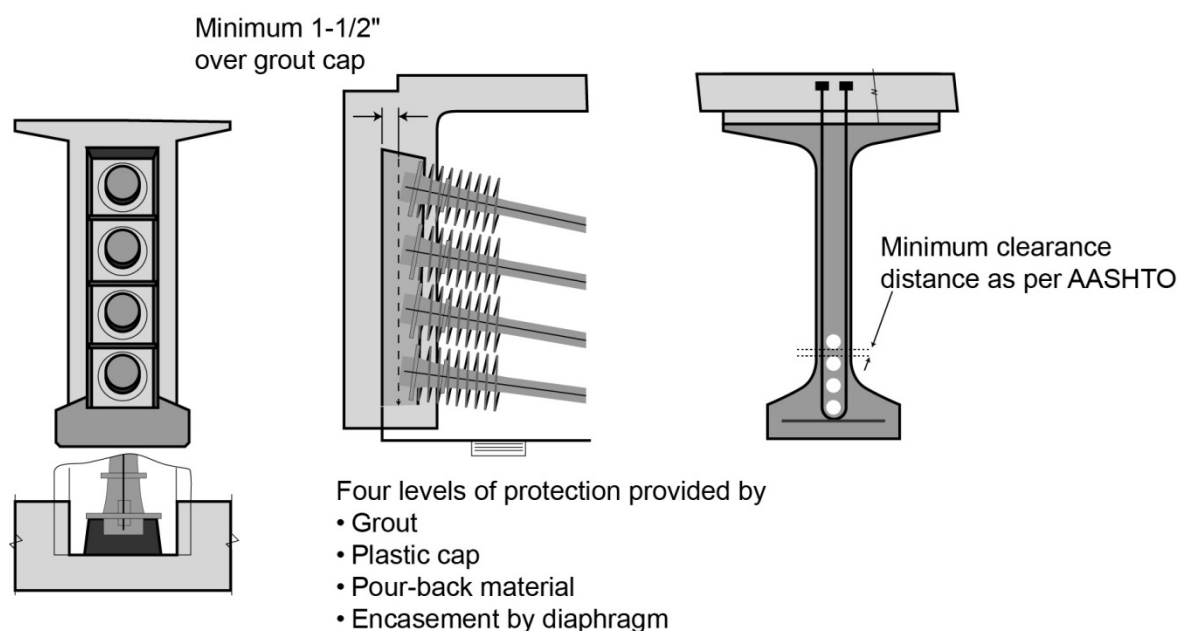
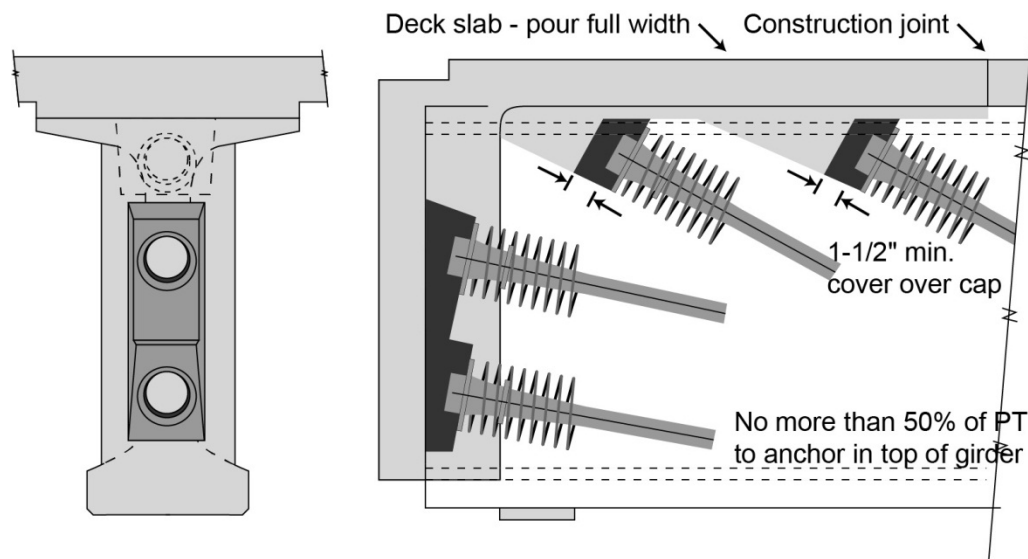


Figure 5.6 – Anchor Protection Details at End Anchorages

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

- 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 5.7) 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.



Four levels of protection provided by

- Grout
- Plastic cap
- Pour-back material
- Structural Deck Slab

Figure 5.7 – Anchor Protection Details at Top Anchorages

- 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 5.8).
- 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.

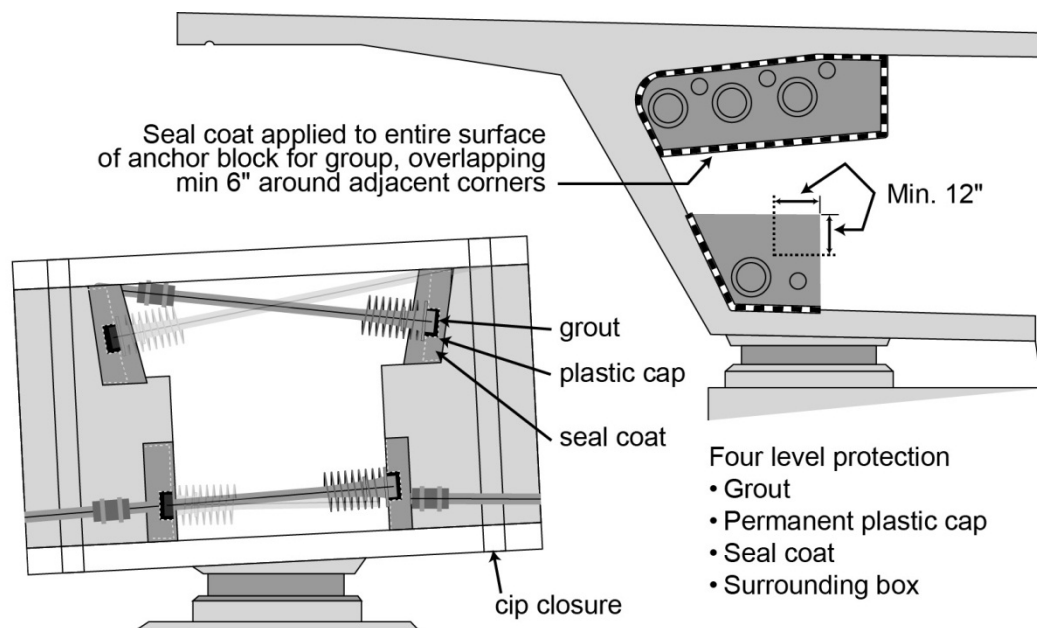


Figure 5.8 – Anchor Protection at Interior Piers

- 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 5.9). (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. Figure 5.10 shows typical details at expansion joint segments in a bridge with external tendons.
- In coastal areas, consider adding skirts or baffles over anchor pour-backs at expansion joints to minimize the direct effect of wind borne spray.

Federal Highway Administration
 Post-Tensioning Tendon Installation and Grouting Manual

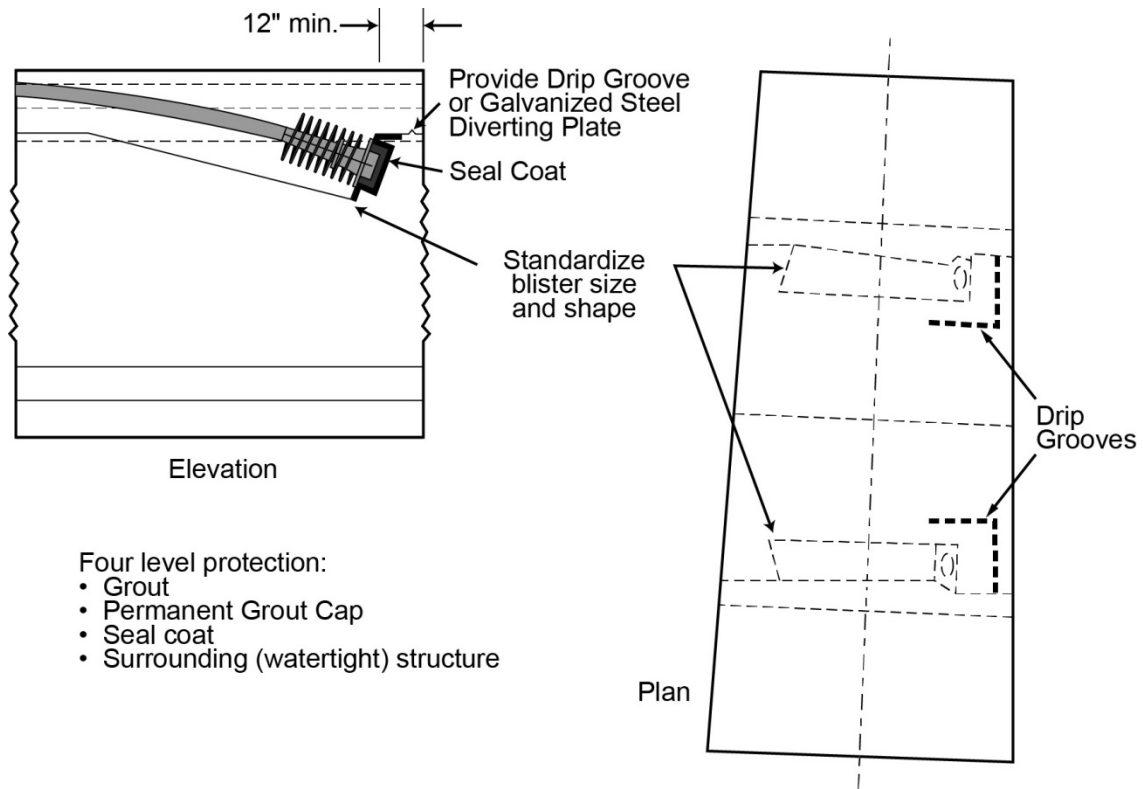


Figure 5.9 – Anchorage Protection for Cantilever Tendons Anchored in Blisters

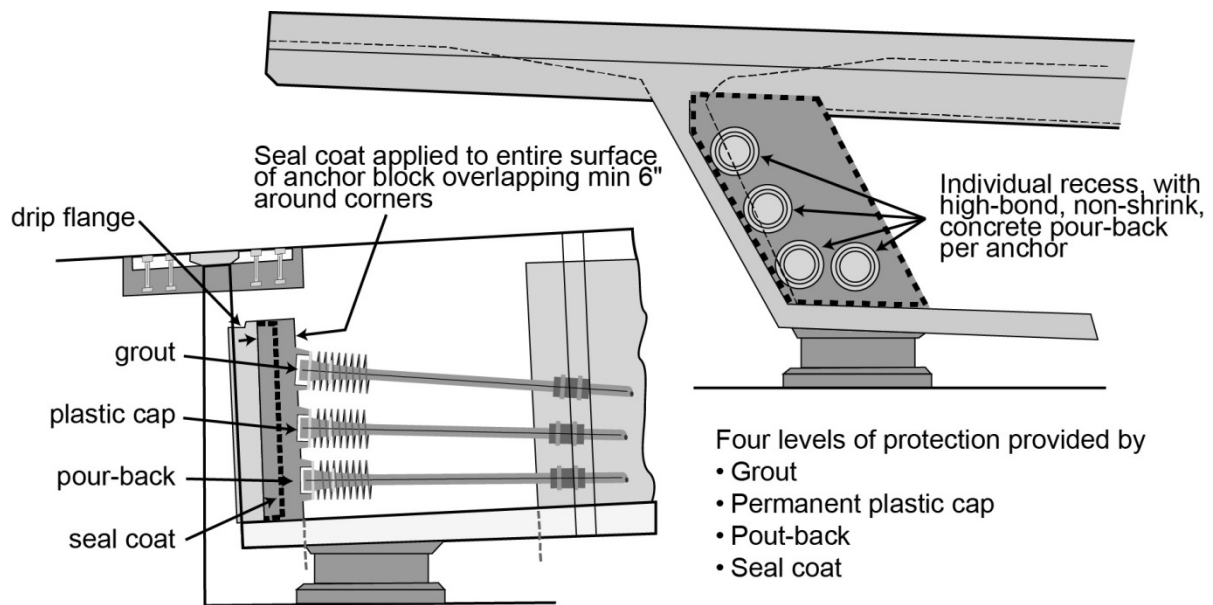


Figure 5.10 – Protection of Anchorages at Expansion Joints

- 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 5.11).

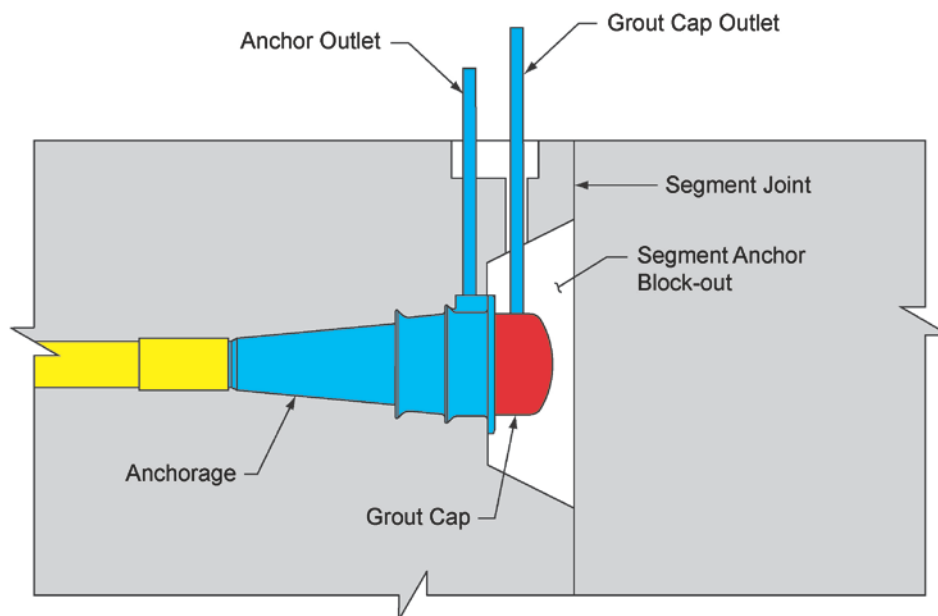


Figure 5.11 – Possible Detail for Embedded Face Anchor

- 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 1/2in 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.

5.5.4 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:

5.5.4.1 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.

5.5.4.2 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.

5.5.4.3 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.

5.5.4.4 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.

5.6 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.

5.7 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, taper 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, provide 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.

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 PTI/ASBI M50.3-12 Specification for Grouting of Post-Tensioned Structures or similar (State Departments of Transportation) specifications.

A.1 Post-Tensioning Systems

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

Anchorage assembly: Mechanical device comprising all components required to anchor the prestressing steel and permanently transfer the post-tensioning force from the prestressing steel to the concrete.

Anchor set: The expected movement of the wedge into the wedge plate or nut into the bearing plate during the transfer of the prestressing force to the anchorage assembly.

Anticipated Anchor Set: The anchor set assumed in the design calculation of the post-tensioning forces immediately after load transfer.

Bar: Bars used in post-tensioning tendons conform to ASTM A722, Standard Specification for Uncoated High Strength Steel Bars for Prestressing Concrete. Bars have a minimum ultimate tensile strength of 150,000 psi (1035 MPa). A Type 1 bar has a plain surface and a Type 2 bar has surface deformations.

Bearing plate: Any hardware that transfers the tendon force into the structure.

Bearing plate, basic: Flat plate bearing directly against concrete meeting the analytical design requirements of PTI (refer to "Acceptance Standards for Post-Tensioning Systems," Section 3.1).

Bearing plate, special: Any hardware that transfers tendon anchor forces into the concrete and does not meet the analytical design requirements of PTI (refer to "Acceptance Standards for Post-Tensioning Systems," Section 3.1).

Confinement reinforcement: Non-prestressed reinforcement in the local zone, usually in the form of spirals, which provide concrete confinement and are considered part of the bearing plate.

Coupler: A device transferring the prestressing force from one partial-length tendon to another.

Duct: Enclosure forming a conduit to accommodate prestressing steel installation and provide an annular space for grout that protects the prestressing steel.

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.

f_{pu} : The nominal ultimate tensile unit stress sometimes referred to as GUTS. When stated as force, F_{pu} , the nominal ultimate tensile unit stress is multiplied by the nominal cross-sectional area of strand or bar.

Post-tensioning: A method of prestressing in which prestressing steel is tensioned after the concrete has reached a specified strength.

Post-tensioning scheme or layout: The pattern, size, and locations of post-tensioning tendons in a structure.

Post-tensioning system (PTS): A particular size tendon, including prestressing steel, anchorages, local zone reinforcement, duct, trumpets, couplers, grout caps, inlets, outlets, all supplied by a single supplier.

Prestressing steel: High-strength steel strand or bar.

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

Strand, seven-wire: Strand conforming to ASTM A416 and consisting of seven wires having a center wire enclosed tightly by six helically placed outer wires with a uniform pitch of not less than 12 and not more than 16 times the nominal diameter of the strand.

Tendon: A single or group of prestressing elements and their anchorage assemblies, which impart the prestress force to a structural member. Also included are ducts, grouting attachments, grout, and corrosion protective materials or coatings.

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

Tendon type: Description of tendon relative to location in the concrete element and/or functional use (that is, internal, external, cantilever, transverse, longitudinal, continuity, stem wall, top slab, and so on).

Wedge: A conically shaped device typically containing two or three pieces, which anchors the strand in the wedge plate.

Wedge plate (anchor head): The hardware that holds the wedges of a multi-strand tendon and transfers the force from the strands to the bearing plate.

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

Zone, anchorage: The portion of the member through which the concentrated prestressing force is transferred to the concrete and distributed more uniformly across the section. Its extent is equal to the largest dimension of the cross section. For anchorage devices located away from the end of the member, the anchorage zone includes the disturbed regions ahead of and behind the anchorage.

Zone, general: 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. The Design Engineer is responsible for the general zone design.

Zone, local: The local anchorage zone is the volume of concrete surrounding and immediately behind 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 local zone design is the responsibility of the post-tensioning system (PTS) supplier. The transverse dimensions of the prism are equal to those of the bearing plate, including any integral confining 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.

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.

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

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 and filtering action of strands and bars.

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 in hours and minutes 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 the flow cone.

Grout: A mixture of cementitious materials and water-with or without mineral additives, admixtures, or fine aggregate- proportioned to produce a pump-able consistency without segregation of the constituents; injected into the duct to fill the space around the tendon strand or bar.

Grout, basic: Cementitious material consisting of cement and water that is proportioned and mixed on site. Class A (refer to PTI's "Specification for Grouting of Post-tensioned Structures").

Grout, engineered: Grout designed and tested for specific performance characteristics (refer to PTI's "Specification for Grouting of Post-Tensioned Structures"). Class B (designed by the manufacturer and mixed on site), Class C (designed by the manufacturer, prepackaged, and mixed on site solely with water), or Class D (special) determined by Design Engineer.

Grout cap, temporary: A device that contains the grout by covering the post-tensioning steel at the wedge plate.

Grout cap, permanent: A device covering the post-tensioning steel and wedge plate at the anchorage that contains the grout and forms a protective cover, sealing the post-tensioning steel and wedge plate at the anchorage.

Initial set: A degree of stiffening of the grout mixture less than the final set, indicating the time in hours and minutes 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.

Post-tensioning: A method of prestressing in which the tendons are tensioned after the concrete has reached a specified strength.

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

Pressure rating: The estimated 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. Commonly referred to as maximum allowable working pressure (MAWP).

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.

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.

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

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, the process being reversible.

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

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 has entered 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 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 (Licensed Design Professional, Engineer of Record, and Design Engineer): The person, firm, or organization engaged by the Owner to prepare the 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 (QA): Actions taken by the Owner or his/her representative to provide assurance to the Owner that the work meets the project requirements and all applicable standards of good practice.

Quality control (QC): Actions taken by the Contractor to ensure that the work meets the project requirements and all applicable standards of good practice.

Subcontractor: A person, firm, or organization engaged by the Contractor to provide select 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.aashto.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.ihc.com)

ASBI: American Segmental Bridge Institute – (For documents, contact: American Segmental Bridge Institute, 142 Cimarron Park Loop, Suite F, Buda, TX, 78610-2837, Phone: 512-523-8214, Fax: 512-523-8213, 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 Diene Monomer (see “External Duct Connections” Chapter 4)
GUTS:	Guaranteed Ultimate Tensile Strength.
HDPE:	Polyethylene (see “Ducts for Tendons”, Chapter 4).
PP:	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, 38800 Country Club Drive, Farmington Hills, MI., 48331, Phone: 248-848-3180, Fax: 248-848-3181, Internet: www.post-tensioning.org)
SS:	Span-by-Span

This Page Intentionally Left Blank

Appendix B – Personnel Qualifications

The installation, stressing and grouting of post-tensioning tendons should be supervised, performed and inspected by personnel with appropriate qualifications and experience. It is recommended that owners ensure the qualifications of the contractor's personnel through either a prequalification process or by requirements specified in standard or project specifications. A prime contractor may also engage specialized sub-contractors with appropriate pre-qualifications to perform the work. Construction Engineering Inspection (CEI) personnel are most often chosen through a merit based selection process. It is recommended that the requirements of this selection process also include specific requirements for pre-qualified personnel.

The following sections are provided to guide in the development of qualifications and experience of key personnel for the construction and inspection of post-tensioned bridges.

B.1 Contractor's Personnel

B.1.1 Project Engineer

The Project Engineer should be a registered Professional Engineer with five years of experience of bridge construction of which three years is in post-tensioned concrete. Experience should include post-tensioning and grouting operations including at least one year in responsible charge of post-tensioning related engineering activities.

B.1.2 Project Superintendent / Manager

The Project Superintendent/Manager should have either a minimum of ten years of bridge construction experience or be a registered Professional Engineer with five years of bridge construction experience in which three years is in post-tensioned concrete construction. Experience should include post-tensioning and grouting operations including at least one year in responsible charge of post-tensioning related operations.

B.1.3 Foreman

The Foreman should have a minimum of five years bridge construction experience including two years in post-tensioning related operations and a minimum of one year as a foreman in responsible charge of post-tensioning related operations.

B.1.4 Crews for Tendon Installation and Stressing

B.1.4.1 Tendon Installation

Personnel shall be certified in accordance with PTI's Level 1 Bonded PT Field Installation program. Crew foreman shall be certified in accordance with PTI's Level 2 Bonded PT Field Specialist program.

B.1.4.2 Tendon Stressing

At least 50% of tensioning personnel shall be certified in accordance with PTI's Level 2 Bonded PT Field Specialist program and remainder of tensioning personnel at least Level 1 Bonded PT Field Specialist program.

B.1.5 Crews for Tendon Grouting

Grouting shall be performed by personnel certified in accordance with the PTI's Level 1 Bonded PT Field Installation program. Grouting operations shall be supervised and under the immediate control of a person certified in accordance with the PTI's Level 2 Bonded PT Field Specialist program and an ASBI Certified Grouting Technician.

For vacuum grouting operations, either the grouting crew foreman or the foreman of a specialist (sub-contractor) vacuum grouting crew should have received training and experience in the use of vacuum grouting equipment.

B.2 Construction Engineering and Inspection (CEI)

B.2.1 Resident Engineer or Senior Project Engineer

The Resident Engineer or Senior Project Engineer should be a registered Professional Engineer with three to five years of experience in general bridge construction and be able to demonstrate knowledge of the importance of post-tensioning and grouting.

B.2.2 Project Engineer

The Project Engineer should be a registered Professional Engineer with three to five years of experience in general bridge construction or be a non-registered engineer with at least eight years in general bridge construction. Of this experience, at least two years should be in post-tensioned bridge construction. This experience should include post-tensioning and grouting operations. In addition, this experience should include one year in responsible charge of the construction inspection of post-tensioned bridge construction and be able to demonstrate knowledge of the importance of post-tensioning and grouting.

B.2.3 Lead Inspector

The Lead Inspector person should have five years of experience of general bridge construction including at least two years in post-tensioned bridge construction. Experience should include monitoring of post-tensioning and grouting operations, including at least one year as the Lead Inspector in responsible charge of inspection.

In addition the Lead Inspector should be certified according to both the "Post-Tensioning Training Course" by the Post-Tensioning Institute (PTI) and "Grouting Certification Course" of the American Segmental Bridge Institute (ASBI) or other equivalent and recognized alternative courses acceptable to the Owner.

B.2.4 Inspector

Inspectors should have at least one year experience in the inspection of post-tensioning and grouting operations and be certified according to both PTI's Level 2 Bonded PT Field Specialist program and "Grouting Certification Course" of the American Segmental Bridge Institute (ASBI) or other equivalent and recognized alternative courses acceptable to the Owner.

Appendix C – Bibliography

AASHTO, “Guide Specifications for Design and Construction of Segmental Concrete Bridges”, American Association of State Highway and Transportation Officials, Second, 1999.

AASHTO, “LRFD Bridge Design Specifications”, American Association of State Highway and Transportation Officials, Second Edition with subsequent interims, 1998.

AASHTO, “Standard Specifications for Highway Bridges”, American Association of State Highway and Transportation Officials, Sixteenth Edition with subsequent interims, 1996.

AASHTO: American Association of State Highway and Transportation Officials, 444 North Capitol Street, N.W., Suite 249, Washington, DC 20001; <http://www.transportation.org>.

ACI Committee 222, “Corrosion of Prestressing Steels,” ACI 222.2R-01, American Concrete Institute, February 2001.

ACI Committee 423, “Recommendations for Concrete Members Prestressed with Unbonded Tendons,” American Concrete Institute, February 1996.

ACI/ASCE Committee 423, “Corrosion and Repair of Unbonded Single Strand Tendons,” American Concrete Institute, February 1998.

Aeberhard, H.U., Buergi, P., Ganz, H.R., et al., “External Post-Tensioning,” VSL Series 1, VSL International Ltd., Berne, Switzerland, 1992.

Anglo-French Liaison Report, “Post-Tensioned Concrete Bridges/ Ponts en Beton Precontraint par Post-Tension,” Highways Agency, Service d’Etudes Techniques des Routes et Autoroutes, Transport Research Laboratory, and Laboratoire des Ponts et Chaussées, Thomas Telford Publishing, London, 1999.

API: American Petroleum Institute, 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: <http://www.global.ihs.com>.

ASBI Grouting Committee, “Interim Statement on Grouting Practices,” American Segmental Bridge Institute, December 4, 2000.

ASBI: American Segmental Bridge Institute, 9201 N. 25th Avenue, Suite 150B, Phoenix, Az., 85021-2721, Phone: 602-997-0064, Fax: 602.997.9965, Internet: <http://www.asbi-assoc.org>.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

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

Ballinger, C.A., Podolny, W., Jr., and Abrahams, M.J., "World Survey of Current Research and Development on Roads and Road Transport, Part II: A Report on the Design and Construction of Segmental Prestressed Concrete Bridges in Western Europe, 1977," Contract No. DOT-FH-11-8893, International Road Federation, Washington, D.C., June 1978.

Barry, R.B. and Bennett, R.N., "The Successful Implementation of Florida's First Post-Tensioned Duct Couplers", 3rd fib International Congress - 2010.

"Cantilever Construction of Bridges," ref: f.i. 2019A, Freyssinet International, Boulogne-Billancourt, France, 1975.

Chaallal, O., Shahawy, M., and Nickas, W., "Corrugated High Density Polyethylene Pipes for Gravity Flow Applications-Service Life and Design Issues," Final Report. Structural Research Center, Florida Department of Transportation, Tallahassee, Florida, April 1999.

Ciolko, A.T., and Tabatabai, H., "Nondestructive Methods for Condition Evaluation of Prestressing Steel Strands in Concrete Bridges," Final Report, NCHRP Project 10-53, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., March 1999.

The Concrete Society, "Durable Post-Tensioned Concrete Bridges," Concrete Society Technical Report 47, Edition 2, Report of a Working Party of the Concrete Society, Berkshire, England, November 2000.

"Corrugated Plastic Ducts for Internal Bonded Post-Tensioning," Technical Report, Bulletin 7, International Federation for Structural Concrete (*fib*), Lausanne, Switzerland, January 2000.

Corven, J. A., "Overview on External Prestressing in the World Application in North America," External Prestressing in Structures Conference, Saint-Remy-les-Chevreuse, France, June 1993.

Corven, J.A., "Mid-Bay Bridge Post-Tensioning Evaluation," Florida Department of Transportation Report, Corven Engineering, Inc., Tallahassee, Florida, 2001.

Corven, J.A. and Moreton, A.J, "New Directions for Florida Post-Tensioned Bridges", Volumes 1 through 9, Florida Department of Transportation Report, Corven Engineering, Inc., Tallahassee, Florida, 2002.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Cullington, D.W., MacNeil, D., Paulson, P., and Elliot, J., "Continuous Acoustic Monitoring of Grouted Post-Tensioned Concrete Bridges," Transportation Research Laboratory, Berkshire, England, UK, and Pure Technologies Ltd., Calgary, Canada.

Davis, A.G., "Nondestructive Evaluation Helps Maintain Concrete Structures," *Structures*, September 2001, pp. 20-25.

DYWIDAG Bonded Post-Tensioning Systems. (Brochure) DYWIDAG Systems International, Bolingbrook, Illinois, May 1998.

DYWIDAG: Multistrand Post-Tensioning System. (Brochure) DYWIDAG Systems International, Bolingbrook, Illinois.

Dywidag Systems International, USA, Inc., Corporate Office, 320 Marmon Drive, Bolingbrook, IL, 60440, 630-739-1100; Fax 630-972-9604; <http://www.dywidag-systems.com>.

"Effect of zinc on prestressing steel", Technical report prepared by a special working group Prestressing steel and zinc of fib Commission 9 Reinforcing and Prestressing Materials and Systems, fib 2012, <http://www.fib-international.org/effect-of-zinc-on-prestressing-steel>.

Elliot, J. F., "Continuous Acoustic Monitoring of Bridges," IBC-99-70, Pure Technologies, Ltd., Calgary, Canada.

Federal Highway Administration, U.S. Department of Transportation, "Bridge Structures Related Research – Summary: Nondestructive Evaluation (NDE) of Highway Bridges," June 1997, March 2, 2001.

Federal Highway Administration, U.S. Department of Transportation, "Performance of Grouts for Post-Tensioned Bridge Structures," December, 1993.

Florida Department of Transportation: "A Guide to the Construction of Segmental Bridges," October, 1989.

Florida Department of Transportation, Standard Specifications, "Section 462: Post-Tensioning", 2003.

Florida Department of Transportation, Standard Specifications, "Section 938: Post-Tensioning Grout", 2002.

Florida Department of Transportation, Standard Specifications, "Section 939: Post-Tensioning System Hardware", 2002.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

Freyermuth, Clifford, "Rational Application of the Elongation Tolerance for Post-Tensioning Tendons" Vol.88, ACI Structural Journal Nov.1, 1992.

Freyssinet International, 1 bis rue du Petit Clamart, 78140, Velizy, France (011)-33-1-46-01-8531, Fax: (011)-33-1-46-01-8681, <http://www.freyssinet.com>, E-mail: jpfuzier@freyssinet.com.

Ganz, H.R., "PT-PLUS: Plastic Duct System," Report No. 241e, VSL International, Berne, Switzerland, May 1991 (Rev. October 1992/R9203005).

General Technologies, Inc. 13022 Trinity Drive, Stafford, TX 77477, 281-240-0990, Fax: 281-240-0990: <http://www.gti-usa.net>.

Ghorbanpoor, A., Borchelt, R., Edwards, M., and Abdel Salam, E., "Magnetic-Based NDE of Prestressed and Post-Tensioned Concrete Members-The MFL System," Publication No. FHWA-RD-00-026, Federal Highway Administration Research, Development, and Technology, U.S. Department of Transportation, McLean, Virginia, May 2000.

Harrison, J. and Krauser, L.B., "New Segmental Duct Coupler for Post-Tensioning Tendons", ASBI Symposium 2008.

Hsuan, Y.G., and McGrath, T., "HDPE Pipe: Recommended Material Specifications and Design Requirements," Report 429, Transportation Research Board, National Academy Press, Washington, D.C., 1999.

IABSE-fip Workshop, "Durability of Post-Tensioning Tendons," Conference Summary, Gant, Belgium, November 15-16, 2001.

Jaeger, B.J., Sansalone, M.J., and Poston, R.W., "Detecting Voids in Grouted Tendon Ducts of Post-Tensioned Concrete Structures Using the Impact-Echo Method," *ACI Structural Journal*, July-August 1996, pp. 462-473.

Kesner, K., and Poston, R.W., "Condition Assessment of Concrete Structures Using Impact-Echo," *Concrete Repair Bulletin*, January/February 1997, pp. 6-11.

Kessler, R.J., Powers, R.G., Langley, R.M., and Zobel, R.s., "Investigation of the Use of High Molecular Weight Methylmethacrylate Monomer for Sealing Various Deck Crack Configurations in the Sunshine Skyway Bridge," Florida Department of Transportation, Bureau of Materials and research, Gainesville, Florida, September 25, 1986.

Kittleman, W. M.; Davis, R. T.; Hamilton, H. R.; Frank, K. H.; and Breen, J. E., "Evaluation of Agents for Lubrication and Temporary Corrosion Protection of Post-Tension Tendons," Research Report 1264-1, Center for Transportation Research, Bureau of Engineering Research, the University of Texas at Austin, Austin, TX, Aug. 1993.

Krauser, L.B., "Achieving Protection of Tendon Enclosures in Segmental Bridge Construction", fib Symposium Prague 2011.

Krauser, L.B., "Improved Performance using Corrugated Plastic Duct in Tight-Radius PT Applications", fib Symposium Prague 2011.

Krauser, L.B., "Segmental Construction - Protecting Internal Post-Tensioning Tendons for 100-year Service Life", 3rd fib International Congress - 2010.

Krauser, L.B., "Selecting Post-Tensioning Protection Levels", fib Symposium Prague 2011.

"Les Fissurations des Betons," Journee d'Etude ITBTP-AFREM-AFB du 5 Juin 1980, *Annales de L'Institut du Bariment et des Travaux Publics*, No. 398, October 1981.

The Liaseal Coupler. (Brochure) Freyssinet, LLC, Chantilly, Virginia, November 2001.

"Magnetic-Based NDE of Prestressed and Post-Tensioned Concrete Members—The MFL System," Federal Highway Administration TechBrief - Report No. FHWA-RD-00-026. Federal Highway Administration Research, Development, and Technology, U.S. Department of Transportation, McLean, Virginia, April 2000.

Manning, D.G., "Durability of Prestressed Concrete Highway Structures," NCHRP Report 140, Transportation Research Board, National Research Council, Washington, D.C., November 1988.

McCormick, J.L., Winter, W.A., and Watkins, R.L., "Methods of Controlling Grout for Prestressed, Post-Tensioned Structures," Interim Report, M & R No. 635117-3, FHWA No. D03-12, State of California Business and Transportation Agency, Department of Public Works, Division of Highways, November 1971.

Mehta, P. K., and Burrows, R.W., "Building Durable Structures in the 21st Century," *Concrete International*, March 2001, pp. 57-63.

Moreton, A., "Special Report: Segmental Bridge Construction in Florida-A Review and Perspective," *PCI Journal*, V. 34, No. 3, May-June 1989, pp.36-67.

Muller, J. M., "Ten Years of Experience in Precast Segmental Construction," *PCI Journal – Special Report*, V. 20, No. 1, January-February 1975, pp. 2-35.

Muller, J. M., and Barker, J., "Design and Construction of the Linn Cove Viaduct," *PCI Journal - Special Report*, V. 30, No. 5, September-October 1985, pp. 2-17.

“New Steeltest® Applications,” *NDT Intelligence Report, No. 2, Spring/Summer 1994*, (Reprint).

NOFX-PEHD Sheathing. (Brochure) PE Spezialisten, Eschborn, Germany.

Paulson, P. O., “Practical Continuous Acoustic Monitoring of Suspension Bridge Cables,” TRB Paper 990893, Pure Technologies Ltd., Pure Technologies, Inc., Calgary, Canada.

PCI Committee on Post-Tensioning, “Recommended Practice for Grouting of Post-Tensioned Prestressed Concrete,” *PCI Journal*, V. 17, No. 6, November-December 1972, pp. 18-25.

Perenchio, W.F., Fraczek, J., and Pfeifer, D.W., “Corrosion Protection of Prestressing Systems in Concrete Bridges,” NCHRP Report 313, Transportation Research Board, National Research Council, Washington, D.C., February 1989.

“Performance of Grouts for Post-Tensioned Bridge Structures,” Publication No. FHWA-RD-92-095, Federal Highway Administration Research and Development, U.S. Department of Transportation, McLean, Virginia, December 1993.

PES IP-DUCT System. (Brochure) PE Spezialisten, Eschborn, Germany.

Podolny, W., Jr., “Corrosion of Prestressing Steels and Its Mitigation,” *PCI Journal*, V.37, No. 5, September-October 1992, pp.34-55.

Podolny, W. Jr., Cox, W.R., Hooks, J.M., et al. “Performance of Concrete Segmental and Cable-Stayed Bridges in Europe,” Report No. FHWA-PL-01-019, Office of International Programs, Federal Highway Administration, U.S. Department of Transportation, May 2001.

Poston, R.W., and Wouters, J.P., “Durability of Precast Segmental Bridges,” Final Report, NCHRP Web Document 15, Project 20-7/Task 92, Whitlock, Dalrymple, Poston, and Associates, Inc., Manassas, Virginia, June 1998.

PTI/ASBI Publication: “Guide Specification for Grouted Post-Tensioning,” PTI/ASBI M50.3-12, Post-Tensioning Institute, First Edition, June 2012.

PTI: Post-Tensioning Institute, 8601 North Black Canyon Highway, Suite 103, Phoenix, AZ 85021, Phone: 602-870-7540, Fax: 602-870-7541, <http://www.post-tensioning.org>.

PTI Publication: “Acceptance Standards for Post-Tensioning Systems,” Post-Tensioning Institute, Fourth Edition, September, 1988.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

PTI Publication: "Anchorage Zone Design," Post-Tensioning Institute, First Edition, October, 2000.

PTI Publication: "Post-Tensioning Manual," Sixth Edition, 2006.

PTI Publication: "Recommendations for Stay-Cable Design, Testing and Installation," Post-Tensioning Institute, Sixth Edition, May, 2012.

PTI Publication: "Specification for Grouting of Post-Tensioned Structures," PTI M55.1-12, Post-Tensioning Institute, Third Edition, April 2012.

Powers, R. G., "Corrosion Evaluation of Post-Tensioned Tendons on the Niles Channel Bridge," State Materials Office, Florida Department of Transportation, Gainesville, Florida, June 29, 1999.

Powers, R.G., Sagues, A.A., and Virmani, Y.P., "Corrosion of Post-Tensioned Tendons in Florida Bridges," Florida Department of Transportation, Tallahassee, Florida, 2001.

"Report on the 1995 Scanning Review of European Bridge Structures," NCHRP Report 381, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C., 1996.

Rogowsky, D.M., and Marti, P., "Detailing for Post-Tensioning," VSL Report Series 1, VSL International Ltd., Berne, Switzerland, 1991.

Sagues, A., "Acoustic and Electrical Evaluation of Post-Tensioned Tendons of the Niles Channel Bridge. Preliminary Findings," Memorandum to Rod Powers, Asst. State Corrosion Engineer, Florida Department of Transportation, July 17, 1999.

Sagues, A.A., and Kranc, S.C., "Initial development of Methods for Assessing Condition of Post-Tensioned Tendons of Segmental Bridges," Final Report, Contract #BC374, Department of Civil and Environmental Engineering, University of South Florida, Tampa, Florida, May 17, 2000.

Salcedo, E., Schokker, A.J., Kreger, M.E. and Breen, J.E., "Bond and Corrosion Studies of Emulsifiable Oils Used for Corrosion Protection in Post-Tensioned Tendons," PTI Journal, Vol. 2, No.1, January 2004.

Sason, A.S., "Evaluation of Degree of Rusting on Prestressed Concrete Strand," *PCI Journal*, V.37, No. 3, May-June 1992, pp. 25-30.

Schokker, A.J., Koester, B.D., Breen, J.E., and Kreger, M.E., "Development of High Performance Grouts for Bonded Post-Tensioned Structures," Draft Copy, Research Report No. 1405-2, Center for Transportation Research, University of Texas, Austin, Texas, June 1999.

Schupack, M., "Grouting Tests on Large Post-Tensioning Tendons for Secondary Nuclear Containment Structures," *PCI Journal*, V. 16, No. 2, March-April 1971, pp.85-97.

Schupack, M., and Suarez, M.G., "Some Recent Corrosion Embrittlement Failures of Prestressing Systems in the United States," *PCI Journal*, V. 27, No. 2, March-April 1982, pp.38-55.

Shahawy, M., "Cracking Investigation of the Acosta Bridge," Florida Department of Transportation Report, Florida Department of Transportation, Tallahassee, Florida, February 2001.

Shaw, P. Pedersen, T.K., and Serluppens, R., "High Energy Radiography Combined with the Agfa Strukturix DPS-Imaging System and Comparison with Other NDE-Method for Inspection of Thick Reinforced Concrete Structures," *NDT.net* - August 2000, V.5 No. 08, Broendby, Denmark, March 2, 2001, <http://www.ndt.net/article/v05n08/shaw/shaw.htm>.

Smith, J.L., and Virmani, Y.P., "Materials and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction," Publication No. FHWA-RD-00-81, Federal Highway Administration Research, Development, and Technology, U.S. Department of Transportation, McLean, Virginia, June 2000.

Smith, L.J. and Wood, R., "Grouting of External Tendons-A Practical Perspective," Proceedings of the Institution of Civil Engineers, *Structures and Buildings*, 146, Issue 1, February 2001, pp. 93-100.

Stain, R.T., and Dixon, S., "Inspection of Cables in Post-Tensioned Bridges," Testconsult Limited, Risley, Warrington, WA3 6QT, August 4, 1999. <http://trid.trb.org/view.aspx?id=409378>.

"Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete," ASTM Designation: A 416-94, 1994.

Vargas, L. M., "Nondestructive Methods for Identification of Voids on Longitudinal Duct Tendons in Segmental Bridges," Beiswenger, Hoch, and Associates, North Miami Beach, Florida, October 1999.

VSL Post-Tensioning Systems. (Brochure) VSL International LTD. Bernstrasse 9, 3421 LYSSACH, Switzerland.

VSL International LTD, "External Post-Tensioning," *VSL Report Series*, 1992.

VSL International LTD, "Detailing for Post-Tensioning," *VSL Report Series*, 1991.

Federal Highway Administration
Post-Tensioning Tendon Installation and Grouting Manual

VSL, Corporate Headquarters: 7455 New Ridge road, Suite T, Hanover, MD 21076, 410-850-7000, Fax: 410-850-4111: <http://www.vsl.net>.

Weaver, R.E., and Freeman, R.J., "Investigation of Field Prestress Grouting Procedures," Interim Report, M & R No. 635117-1, FHWA No. D03-12, State of California Business and Transportation Agency, Department of Public Works, Division of Highways, November 1971.

Weaver, R.E., McCormick, J.L., Watkins, R.L., and Freeman, R.J., "Laboratory Investigation of Grout for Prestressed, Post-Tensioned Structures," Interim Report, M & R No. 635117-2, FHWA No. D03-12, State of California Business and Transportation Agency, Department of Public Works, Division of Highways, November 1971.

Williams Form Engineering Corporation, Main Office: 280 Ann Street, Grand Rapids, MI 49504, 616-365-9220, Fax: 616-365-2668, <http://www.williamsform.com>.

Yazdani, N., "Epoxy Jointing of Concrete Segments," WP Item No. 0510736, Florida A & M University – Florida State University College of Engineering, Tallahassee, Florida, July 1997.

This Page Intentionally Left Blank.