Florida Department of Transportation

New Directions for Florida Post-Tensioned Bridges

Volume 1 of 10:
Post-Tensioning In Florida Bridges

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Preface

As a result of recent findings of corrosion of prestressing steel in post-tensioned bridges, the Florida Department of Transportation will be changing policies and procedures to ensure the long-term durability of post-tensioning tendons. The background to these revised policies and procedures is presented in this study entitled, *New Directions for Florida Post-Tensioned Bridges*. The study will be presented in five volumes, with each volume focusing on a different aspect of post-tensioning.

Volume 1: Post-Tensioning in Florida Bridges presents a history of post-tensioning in Florida along with the different types of post-tensioned bridges typically built in Florida. This volume also reviews the critical nature of different types of post-tensioning tendons and details a new five-part strategy for improving the durability of post-tensioned bridges.

Volume 2: Design and Detailing of Post-Tensioning in Florida Bridges applies the five-part strategy presented in Volume 1 to the design of post-tensioned bridges in Florida. Items such as materials for enhanced post-tensioning systems, plan sheet requirements grouting, and detailing practices for watertight bridges and multi-layered anchor protection are presented in this volume.

Volume 3: Construction Inspection of Florida Post-Tensioned Bridges addresses the five-part strategy for the various types of post-tensioned bridges in Florida, but from the perspective of CEI. The various types of inspections required to fulfill the five-part strategy and checklists of critical items are presented.

Volume 4: Condition Inspection and Maintenance of Florida Post-Tensioned Bridges addresses the specifics of ensuring the long-term durability of tendons in existing and newly constructed bridges. The types of inspections and testing procedures available for condition assessments are reviewed, and a protocol of remedies are presented for various symptoms found.

Volume 5: Load Rating Segmental Post-Tensioned Bridges in Florida provides guidance for meeting AASHTO LRFD load rating requirements as they pertain to precast and cast-in-place segmental bridges.

Disclaimer

The information presented in this Volume represents research and development with regard to improving the durability of post-tensioned tendons; thereby, post-tensioned bridges in Florida. This information will assist the Florida Department of Transportation in modifying current policies and procedures with respect to post-tensioned bridges. The accuracy, completeness, and correctness of the information contained herein, for purposes other than for this express intent, are not ensured.

Volume 1 – Post-Tensioning In Florida Bridges

Contents

Chapter 1 – Introduction

The State of Florida has been, and continues to be, a leader in the development of prestressed concrete bridges in the United States. There are 72 major post-tensioned bridges in Florida with a total deck area of nearly 16 million square feet built over the last 46 years. Currently there are 4 major post-tensioned bridges under construction with a bid value in excess of $180 million. Discovery of corrosion in a few post-tensioned Florida bridges initiated a series of inspections and investigations in late 2000 and early 2001, the goal of which were to better understand the condition and anticipated durability of these bridges. Similar experiences and studies have been undertaken recently in Europe with similar goals.

This document is the first of five Volumes being produced to promote enhanced durability of post-tensioned concrete bridges in Florida. These documents represent the collective findings of the Florida Department of Transportation and a consultant workforce. The five Volumes, each focusing on a different aspect of post-tensioning are:

Volume 1: Post-Tensioning in Florida Bridges
Volume 2: Design and Detailing of Post-Tensioning in Florida Bridges
Volume 3: Construction Inspection of Florida Post-Tensioned Bridges
Volume 4: Condition Inspection and Maintenance of Florida Post-Tensioned Bridges
Volume 5: Load Rating Segmental Post-Tensioned Bridges in Florida

In *Volume 1: Post-Tensioning in Florida Bridges*, a history of post-tensioning in Florida is presented along with the different types of post-tensioned bridges typically built in Florida. This volume also reviews the critical nature of different types of post-tensioning tendons and details a new five-part strategy for improving the durability of post-tensioned bridges.

Volume 2: Design and Detailing of Post-Tensioning in Florida Bridges applies the five-part strategy presented in Volume 1 to the design of post-tensioned bridges in Florida. Items such as materials for enhanced post-tensioning systems, plan sheet requirements grouting, and detailing practices for watertight bridges and multi-layered anchor protection are presented in this volume.

The third volume entitled *Volume 3: Construction Inspection of Florida Post-Tensioned Bridges* also addresses the five-part strategy for the various types of post-tensioned bridges in Florida, but from the perspective of Construction Engineering Inspection (CEI). The various types of inspections required to fulfill the five-part strategy and checklists of critical items are presented.

Volume 4: Condition Inspection and Maintenance of Florida Post-Tensioned Bridges addresses the specifics of ensuring the long-term durability of tendons in existing and newly constructed bridges. The types of inspections and testing procedures available for condition assessments are reviewed, and a protocol of remedies are presented for various symptoms found.

The fifth volume being developed is *Volume 5: Load Rating Segmental Post-Tensioned Bridges in Florida*. The information in this volume will provide guidance for meeting AASHTO LRFD load rating requirements as they pertain to precast and cast-in-place segmental bridges.

1.1 Fundamental Principles

Prestressed concrete construction is the technique of precompressing concrete members to offset anticipated tensile stresses resulting from subsequently applied loads. Prestressing forces are applied to hardened concrete by transferring tensile forces that have been introduced into high strength steel elements. Prestressing is typically achieved by one of two methods, pretensioning and post-tensioning, or a combination of the two.

In pretensioned concrete members, the high strength tensile elements (typically prestressing strands) are stressed through the forms before the concrete is cast. The strands are released after the concrete has been cast and allowed to gain sufficient strength, transferring through bond an equal and opposite compression into the member.

Over the years, much research, analysis and testing has been undertaken to develop a high level of confidence in pretensioned concrete construction in Florida. Limitations of pretensioned construction such as long spans, highly curved structures and difficult construction site access, have led designers to develop new methods of building concrete bridges. These methods call for the use of post-tensioning.

In post-tensioned concrete construction, the high strength elements (post-tensioning tendons) are stressed against the hardened concrete by means of hydraulic jacks. Anchorages at each end of the tendon lock the force in the tendons and induce an equal and opposite compressive force in the concrete.

Post-tensioning tendons are typically made of a high strength steel bar or a number of high strength steel, 7-wire prestressing strands (six small diameter wires helically wound around the seventh central “king” wire). Post-tensioning tendons may be installed through voids formed by ducts cast into the concrete – in which case, they are *internal* tendons - or they may be installed outside the concrete itself - in which case they are *external* tendons. Ducts for internal tendons are usually made of corrugated metal or plastic. External tendons are most often used in span-by-span segmental construction. They anchor in diaphragms at each end of each span and drape through deviators at intermediate points in the span. At diaphragms and deviators, external tendons are housed in rigid steel pipes pre-bent to specified radii and cast into the concrete. Between these points, where the tendon is external to the concrete, the tendons are inside high-density polyethylene (HDPE) smooth pipes. Some tendons have been detailed to be internal over a portion of their length and external over the remainder of the tendon.

The annular area between the prestressing steel and duct of the post-tensioning tendon is grouted after stressing. The two primary functions of the grout are bond development and corrosion protection. The effectiveness of the grout in relation to these two primary functions is tied to several parameters such as the type of construction (cast-in-place vs. precast segmental), the type of tendon (internal vs. external) and quality of grout and grouting procedures.

1.2 History and Development of Post-Tensioned Bridges in Florida

The Florida Department of Transportation has been a pioneering force in the development and use of post-tensioned bridge construction. The first use of post-tensioning in Florida bridges was nearly fifty years ago. Since that time important innovations have enhanced the Department’s ability to cost effectively meet the demands of the State’s growing transportation needs. This section presents an overview of the history and usage of post-tensioned bridge construction in Florida. This history traces the introduction of the following important bridge types:

- Early post-tensioned beam bridges
- Span-by-span segmental bridges
- Precast balanced cantilever bridges
- Continuous and spliced girder bridges
- Cast-in-place post-tensioned bridges

More complete details of each of the major post-tensioned bridges in Florida can be found in Appendix B (a separate document to this Volume).

1.2.1 Early Post-Tensioned Beam Bridges

Sunshine Skyway Bridge Approaches (1954)

Post-tensioning using tendons was first introduced in Florida in 1954 by then Bridge Engineer, Bill Dean. Bar tendons were used in the precast I-beams for the low-level trestle approaches to the original Sunshine Skyway Bridge crossing Tampa Bay. There were three, 1-inch diameter, 160 ksi, McCalloy bars in the bottom flange of each beam. Each bar was placed in a separate duct and grouted after stressing.

An inspection in 1971 found corrosion in a few of the girders. The corrosion was a result of insufficient concrete cover at some end anchor blocks, exposing the post-tensioning to salt spray and deck runoff through deteriorated deck joints. In some cases, water had penetrated the anchor blocks and initiated some local pitting corrosion in the post-tensioning bars. In 1973, six beams were removed and load tested to failure at the University of Florida. The beams reached their design strengths. Routine maintenance inspection was implemented to monitor the long-term behavior of the remainder of the approach bridges. The new Sunshine Skyway Bridge replaced these structures in 1987. Much of the trestle remains intact and now serves as part of the recreational facility.

Sebastian Inlet (1965)

Though eventually built as a totally pretensioned bridge, the Sebastian Inlet Bridge (Figure 1.1) represented a significant early Florida post-tensioned bridge design. The bridge is a statically determinate, cantilever and suspended span structure with side spans of 100 feet and a main span of 180 feet.

The superstructure of the three-span main unit is made of variable depth I-girders. Each line of variable depth I-girders is made of 5 precast beam elements. The end beams reach from the side piers to splice locations 35 feet from the main piers. The 65-foot long cantilever beams located over the channel piers vary from 6 feet to 9 feet in depth are spliced with the end beams, and cantilever 30 feet into the main span. The fifth beam is a 120-foot pretensioned drop-in beam supported by cantilever beams resting on the main piers. During construction, temporary bents supported the elements in the side-span prior to pouring the closure joints (Figure 1.2).

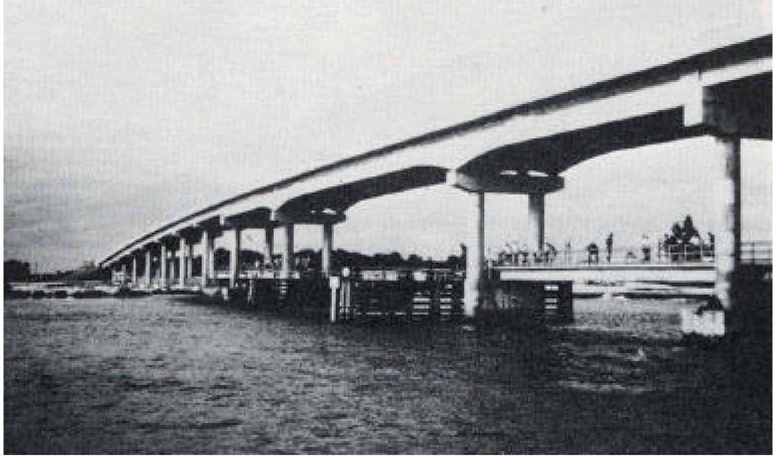

Figure 1.1 - Sebastian Inlet Bridge

The end beams of the side spans and the drop-in span were designed to be entirely pre-tensioned with 0.5-inch diameter straight and deflected (depressed) strands. The variable depth portion that cantilevers over each pier was designed to be post-tensioned using 15 tendons each comprising 18 wires of 0.196-inch diameter high strength steel. The tendons draped over the top at the pier and anchor at the ends of the variable depth cantilever portion. Two of these tendons were to be post-tensioned after casting for shipping and erection - the rest were post-tensioned in phases as the construction of the deck proceeded.

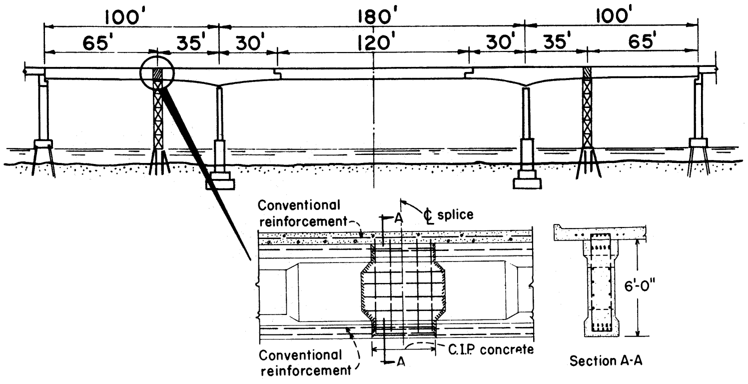

Figure 1.2 - Temporary Bent Location and Splice of the Sebastian Inlet Bridge

During construction, the Contractor made use of special provisions that permitted changing the prestressing of the variable depth members from post-tensioning to pretensioning. This three span concept was repeated for the Dupont Bridge over St. Andrews Bay near Panama City, Florida (opened circa 1966). Post-tensioning tendons in these bridges were grouted using a grout formulation from the 1959 Standard FDOT Specifications. This specification called for a grout composed of cement mixed with fly ash and sand.

Chipola Nursery Road (1979) and other Post-tensioned AASHTO I-Girder Bridges

Chipola Nursery Road Bridge over I-10 near Marianna (Figure 1.3) represents Florida's first use of draped post-tensioning tendons installed in the webs of precast pre-tensioned AASHTO girders. This bridge, designed by the FDOT Central Office, is a two span continuous girder bridge superstructure. Tendons run from one end of the bridge to the other through four AASHTO Type IV precast girder sections. The four girder sections are connected by three cast-in-place concrete connections, two at the mid-spans and one over the median pier. Temporary piers were used to support the girder elements during construction. All tendons are internal and grouted after post-tensioning.

The continuity achieved through the addition of the post-tensioning allowed longer span lengths and eliminated permanent piers adjacent to the outer shoulders of I-10. As a result of the success of this project, the two span continuous girder concept was successfully adopted for subsequent structures in Florida.

Figure 1.3 – Chipola Nursery Road Bridge over I-10

1.2.2 Span-by-Span Segmental Bridges

The span-by-span method of erecting precast segmental bridges is so named because the concrete segments of an entire span are erected on a temporary support system that spans from one pier to the next. After the segments are placed, a closure joint is made adjacent to the pier segments and post-tensioning tendons stressed, making the span self-supporting. This allows the temporary support system, typically a steel truss under the bridge or gantry over the top, to move on to the next span, allowing the repetitive sequence to continue.

Span-by-span erection evolved from earlier segmental bridges, mostly in Europe, erected in precast balanced cantilever using overhead, self-launching erection gantries. By the 1970's, such systems were able to erect cantilevers up to 300 feet in length in two to three weeks. The speed of construction was limited by the time required to install and stress the cantilever post-tensioning for each pair of segments added in cantilever. The span-by-span method enables the erection of complete spans with lengths up to 150 feet in a single day. The key to achieving these rates of construction is the use of full span external tendons. The tendons are draped through deviation saddles and overlapped in the top of the pier segments to make one span continuous with another. In addition, with all tendons external to the concrete, epoxy used to seal the joints between precast segments was not needed.

The first application of span-by-span construction in Florida, as well as the United States, was in 1979 for the Long Key Bridge (Figure 1.4). Three other bridges in the Florida Keys, the Seven Mile, Channel Five, and Niles Channel Bridges were subsequently built using the span-by-span method. Spans of 118 feet were selected at Long Key to match the span of two arches of the adjacent existing highway (and previously rail) bridge that was to remain a local recreational amenity. The same superstructure cross section used for the Long Key Bridge was used for the Seven Mile Bridge; however, longer spans of 135 feet were selected for the Seven Mile Bridge. During construction, the anticipated rapid rate for span-by-span erection was achieved in these bridges. Additional cost savings for these bridges were made possible by using smaller piers and foundations. Wide pier caps and multiple columns that are normally required for beam and slab construction are not needed in segmental construction using trapezoidal box girders.

Figure 1.4 – Long Key Bridge

In 1983 the high level approaches to the New Sunshine Skyway Bridge were built in a similar fashion. Since then, two more highway bridges, Mid-Bay (1994) over Choctawhatchee Bay near Destin, Florida, and Garcon Point (1998) near Pensacola have been built using span-by-span construction. The newly completed Evans Crary Bridge in Stuart, Florida used the span-by-span method to achieve span lengths of 180 feet.

1.2.3 Precast Segmental Balanced Cantilever Bridges

As work progressed in the Florida Keys, the first precast segmental balanced cantilever bridge in Florida, carrying Ramp I over the I-75 (1984) was constructed. The Ramp I Bridge (Figure 1.5) is a 9-foot 4-inch deep, trapezoidal box girder with continuous spans up to 224 feet. The balanced cantilever method of construction begins with the placement of the pier table, the precast elements directly over the supporting pier. Matching pairs of segments, one on either side of the pier table, are erected and post-tensioned to the pier table with cantilever tendons. Temporary support frames adjacent to the pier provide stability to the growing cantilever. When cantilevers from adjacent piers reach mid-span, a concrete closure joint is poured and continuity tendons stressed, completing the span.

Figure 1.5 – Ramp I Bridge

Later in the 1980's, several similar precast segmental balanced cantilever bridges were built using the same construction scheme. Fifteen balanced cantilever bridges were built at two major interchanges between I-595 and I-75 and US 441. Four access bridges, from U.S. 1 into and out of the Fort Lauderdale International Airport, and two other bridges at the Palmetto Interchange were also built using the balanced cantilever method.

Each of these bridges is a continuous constant depth trapezoidal box, with spans lengths reaching over 200 feet. Most of the bridges carried one or two lanes of traffic with shoulders. Wider highway widths were made by erecting parallel box girders and connecting them with a longitudinal cast-in-place closure strip. All segments were precast off-site, trucked to the site and erected using cranes from the ground. A few of the very long, early bridges have structural "dapped" hinges at quarter-points of some spans. This detail proved troublesome and some cracking was experienced. Repairs were implemented and these continue to function satisfactorily today.

Contemporary with the above projects in south Florida, the side-spans adjacent to the cable-stayed spans of the New Sunshine Skyway Bridge (1987) (Figure 1.6) were erected in precast balanced cantilever. A beam and winch system fabricated specifically for the project lifted precast segments weighing up to 300 tons while stabilizing beams spanned from one pier to the next, carrying temporary out-of-balance effects during construction.

Figure 1.6 – Balanced Cantilever Side Spans of the Sunshine Skyway Bridge

The Dodge Island, Bridge (1991), shown in Figure 1.7, was the first bridge built in Florida having precast segments with three webs. Two parallel structures carry the eastbound and westbound roadways of this important connection to the Port of Miami. The 3-web box was chosen to carry the 58-foot wide bridge deck of each structure. Span lengths range up to 220 feet using a constant depth box of 9 feet 3inches. Each bridge is approximately 2,500 feet long and is divided into two continuous units with an expansion joint centered at an interior pier rather than at a quarter point. Segments were precast off-site and erected using a barge mounted crane.

Figure 1.7 – Dodge Island Bridge at the Port of Miami

Precast balanced cantilever construction has been used for several other structures in Florida. Several others are currently in design or under construction.

1.2.4 Continuous and Spliced Precast Girder Bridges

The concept of using post-tensioning in I-girders, originally used in the late 1970's (Section 1.2.1), was applied by FDOT to develop Florida Bulb-Tee girder bridges. Eau Gallie Bridge (Figure 1.8), completed in 1988, was the first Florida bridge built with continuous bulb-tee girders. These precast girders combine straight pre-tensioning strands in the bottom flange and post-tensioning tendons of multiple strands draped in the webs. Each girder was pre-tensioned sufficiently at the precast plant to carry its own weight for transport and erection. When erected, it was made continuous with the beam in the next span through a cast-in-place joint that was a part of the transverse diaphragms connecting the ends of the beams over each interior pier. Longitudinal post-tensioning tendons extend and drape through four continuous spans in ducts cast into the webs and spliced over the piers. The post-tensioning tendons were stressed in phases; one half of the tendons were stressed before the deck slab was cast and the other half afterward. All tendons are internal and were grouted after stressing.

Figure 1.8 – Eau Gallie Bridge

The same concept was later used for the Howard Frankland Bridge in Tampa, the Edison Bridge in Fort Myers and SR 83/US 331 across Choctawhatchee Bay.

The method of making bulb-tee girders continuous through the use of post-tensioning has been extended from constant depth bridge units of repetitive span length to variable depth precast cantilever girders made continuous by post-tensioning through cast-in-place splices. The approach to construction is very similar to the early Sebastian Inlet Bridge and the Dupont Bridge, except that the central precast element is made integral with the remainder of the precast girders using post-tensioning tendons that run the full length of the three-span unit. Figure 1.9 shows the placement of one of the variable depth precast girders for the Flagler Beach Bridge in Flagler County. This method has allowed the construction of three span units with central spans up to 320 feet.

Figure 1.9 – Flagler Beach Bridge, Flagler County

1.2.5 Cast-In-Place Post-Tensioned Bridges

Currently, the Acosta Bridge in Jacksonville (1992) (Figure 1.10) is the only cast-in-place segmental balanced cantilever bridge in Florida. Each of the parallel structures utilizes a three-web box girder up to 35 feet deep and 75 feet wide. The central five-span continuous structure has a main span of 630 feet. Superstructure cantilever segments were cast in lengths up to 16 feet using form travelers. All spans are post-tensioned with internal grouted, multi-strand, cantilever and continuity tendons. Parts of the superstructure webs near the piers are post-tensioned with vertical bars. In addition to longitudinal post tensioning, the top slab is also transversely post-tensioned as with precast segmental construction.

Figure 1.10 – Acosta Bridge in Jacksonville, Florida

The cycle time for the construction of one segment at each end of the cantilever was about one week. Segments were constructed on each end of a cantilever in an arrangement laid out to be no more than one half of a segment out-of-balance at any time. Temporary stability towers carried out-of balance construction effects to the main foundations. The end spans of the five span unit of the Acosta Bridge (Figure 1.11) were cast-in-place on falsework.

A few other cast-in-place concrete bridges were built using falsework and post-tensioning over the entire structure length. Other bridges built in this fashion include the Countryside Boulevard (US-19 (SR-55), 1994), SR-687 over I-275, SR-93 (1995) in Tampa and the Hallandale Beach Boulevard connector to SR A1A. These feature continuous, hollow section box superstructures with two or more webs containing internal, grouted tendons.

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Figure 1.11 – Cast-in-place on Falsework Spans of the Acosta Bridge

Low-level trestle approaches to the Broadway Bridge, built with cast-in-place construction, have recently been completed. The 40-foot span lengths vary in depth from 24 inches at supports to 18 inches at midspan. The slab spans were cast-in-place on falsework and longitudinally post-tensioned to make 8 continuous spans.

1.3 Post-Tensioned Bridge Repairs in Florida

This section provides a brief overview the Department's findings of corrosion and repairs performed for post-tensioned bridges in Florida. The study of these incidences of post-tensioning corrosion have led to increased design awareness, strengthened construction specifications, improved procedures for maintenance, inspection and repairs.

1.3.1 Seven Mile Bridge

Through the 1980's and early to mid 1990's there was a minimum of maintenance required to the post-tensioned bridges in Florida. The expansion joints selected for the span-by-span bridges in the Florida Keys did not perform well and had to be replaced. Precast segmental box girders of the Keys Bridges were typically prestressed transversely with pretensioning. The box girder of the Seven Mile Bridge was the only one of these brides that was constructed using reinforced concrete. The girder experienced significant longitudinal cracking in the deck over the webs due to transverse flexure and had to be sealed.

1.3.2 I-595/I-75 Interchange

District 4 in Broward County did have an ongoing maintenance effort in some of the balanced cantilever post-tensioned bridges at the I-595/I-75 Interchange built between 1986 and 1989. Inspections of these bridges, beginning in 1992, routinely reported water leaking through the epoxied joints (Figure 1.12) and efflorescence coming from the top slab continuity tendons. Efforts were taken to locate the source of the leaks, and in doing so prevent further leakage of water, cracking of protective pour backs and some additional efflorescence. Additional investigations found one top continuity tendon in excess of 300 feet to be substantially without grout. The result was to drill multiple holes through the deck into the duct and FDOT crews injected the duct with grout in 1996. At this point in time the FDOT believed that these circumstances were isolated incidences that could be attributed to a poor construction and inspection practices.

Figure 1.12 – Epoxy Joint Leaking in the I-595/I-75 Interchange

1.3.3 Niles Channel Bridge

In the summer of 1999 a routine inspection of the Niles Channel Bridge revealed that a longitudinal post-tensioning tendon, one of 6 in each span, had failed. A 9-inch movement of the tendon through one of the deviation saddles was noticed first (Figure 1.13). The boot connecting the polyethylene duct to the steel pipe at the expansion joint diaphragm was opened and active corrosion was found on the prestressing strands in this tendon.

Considering the impact of loosing one tendon of the six in each span, and that these bridges provide the only access to the Florida Keys, the failed tendon was immediately replaced. Examination of the removed tendon indicated a void in the grout and heavy pitting of the prestressing strands inside the anchor head (Figure 1.14). Initially, the corrosion was attributed to excessive bleed water at grout/void interface. Further investigation indicated that cyclical recharge of the void in the anchor head by water contaminated by wind-born ocean salt spray was a primary cause of tendon corrosion. The contaminated water leaked through the expansion joints and ran down the inside faces of the segment diaphragms onto the anchorages. Evidence of this recharge is seen in water staining on the concrete surrounding the anchor face (Figure 1.15). The circumstances found were very important, but by and large the problem was believed to be an isolated case

Figure 1.13 – Plan View of Slipped Tendon at Deviation Saddle

Figure 1.14 – Advanced Corrosion of Strands within Niles Channel Anchorage

Figure 1.15 – Anchorage of the Failed Tendon At Niles Channel with Water Staining from Leaking Expansion Joint

Prompted by the findings at the I-595/I-75 Interchange and the Niles Channel Bridge, the Florida Department of Transportation initiated actions to better understand the condition of post-tensioning in Florida bridges. Vibration methods were utilized at the Niles Channel Bridge for determining forces in stressed external cables. Magnetic Flux Leakage methods were utilized to help locate corrosion and section loss in external tendons. Impact-Echo methods were studied to help locate grout voids in internal tendons at the I-595/I-75 Interchange.

Design requirements and specifications for the grouting of new post-tensioned bridge construction were also strengthened. Important steps taken in the fall of 1999 included:

- Considered and encouraged use of pre-bagged dry components of grouts to control quality and consistency on site.
- Bottom-up grouting specified in all projects to minimize void development through actions such as cavitation.
- Vent locations to be shown on plans submitted by the Contractor and the requirement that the designer envision and show one workable sequence for grout injection.
- Enhanced training of construction inspection personnel.

1.3.4 Mid-Bay Bridge

The next incidence of post-tensioning corrosion discovered was on the Mid-Bay Bridge, opened to traffic in 1993 (Figure 1.16). The 19,265-foot long bridge, opened to traffic in 1993, was undergoing an annual inspection on August 28, 2000 when two failed tendons, one in Span 28 and one in Span 57, were discovered.

The failed tendon of Span 28 was different in its nature than that previously observed at the Niles Channel Bridge. The failure had come at a corrosion cell that had grown in the free length of the tendon away from anchorages (Figure 1.17). This failure could not be traced to the corrosion of strands in the void of an anchor head; rather, a breach in the duct itself resulted in access of moisture and development of isolated corrosion.

Figure 1.16 – The Mid-Bay Bridge

Figure 1.17 – Failure of Tendon 28-6 on the Mid-Bay Bridge

The failure of the tendon in Span 57 (Figure 1.19) was similar to the failure at the Niles channel Bridge. Corrosion of strands in the anchor head progressed to the point that strands in the tendon fractured. The bond between the grouted portion of the duct and the failed tendon was sufficient to pull the tendon and steel pipe from the expansion joint segment diaphragm.

Figure 1.18 – Failure of Tendon 57-1 on the Mid-Bay Bridge (At Expansion Joint Diaphragm)

Based on the findings of these two failed tendons, the FDOT launched a series of emergency inspections that included: visual crack inspection of all ducts, sounding of the ducts, borescope investigations of all 1728 anchorages, mag-flux testing of all tendons, and vibration testing of all tendons. These inspections identified a number of deficiencies in the post-tensioning tendons of the Mid-Bay Bridge as documented in the report entitled *Mid-Bay Bridge Post-Tensioning Evaluation* dated October 10, 2001. As a result, eleven excessively corroded tendons were replaced, anchor voids were vacuum injected with grout and anchor head protection was restored. Bids for a construction contract for a complete wrapping of all the external tendons were received on August 31, 2001.

The Mid-Bay Bridge experience led the FDOT to issue temporary design memoranda to further enhance the durability of post-tensioning tendons. These memoranda required the use of pre-bagged grouts, inspection of tendon anchorages after grouting and the use of anchor blisters for cantilever tendons in balanced cantilever bridges. Cantilever tendons anchored on the faces of segments were allowed provided the Contractors grout and inspect the grouted anchorages prior to assembling the next segments in cantilever.

1.3.5 Sunshine Skyway Bridge

The most recent discovery of post-tensioning corrosion was in the precast segmental columns of the high level approaches of the Sunshine Skyway Bridge in Tampa, Florida, opened to traffic in 1987. The precast segments of these hollow piers are nearly elliptical in shape but vary in dimension as a function of column height. The vertical post-tensioning is a mix of both internal and external tendons. On September 21, 2000 the FDOT found a failed tendon in Pier 133 North (Figure 1.20). The FDOT retained a consultant team to perform extensive inspection and testing of the post-tensioning of the Sunshine Skyway piers. Pier 133 North has been rehabilitated by the addition of mild reinforcing doweled into the support footings and the core of the hollow pier filled with concrete. The final report of the evaluation of the post-tensioned piers of the Sunshine Skyway Bridge is under final review and will soon be available through the Department.

Figure 1.19 – Tendon Corrosion in the Sunshine Skyway Bridge Piers

Chapter 2 – Applications of Post Tensioning by Bridge Type

This chapter presents various types of post-tensioning tendons used in Florida. Longitudinal post-tensioning tendons are presented by bridge type. Other superstructure tendons, such as transverse post-tensioning and diaphragm reinforcing, are provided in separate sections of this chapter. Post-tensioning tendons for substructure construction are presented at the end of this chapter.

2.1 Precast Segmental Balanced Cantilever Bridges

Precast segmental balanced cantilever construction involves the symmetrical placement of segments about a supporting pier. Each segment is lifted into position and joining faces are coated with epoxy. Temporary post-tensioning bars are then stressed attaching the segment to the cantilever. When both balancing segments are in place, post-tensioning tendons are stressed across the cantilever. In this way, as segments are added to the cantilever, more top cantilever tendons are added. The number of cantilever tendons is a maximum at the segment over the pier and reduces along the length of the cantilever. Figure 2.1 shows two typical methods of placing precast segments in balanced cantilever.

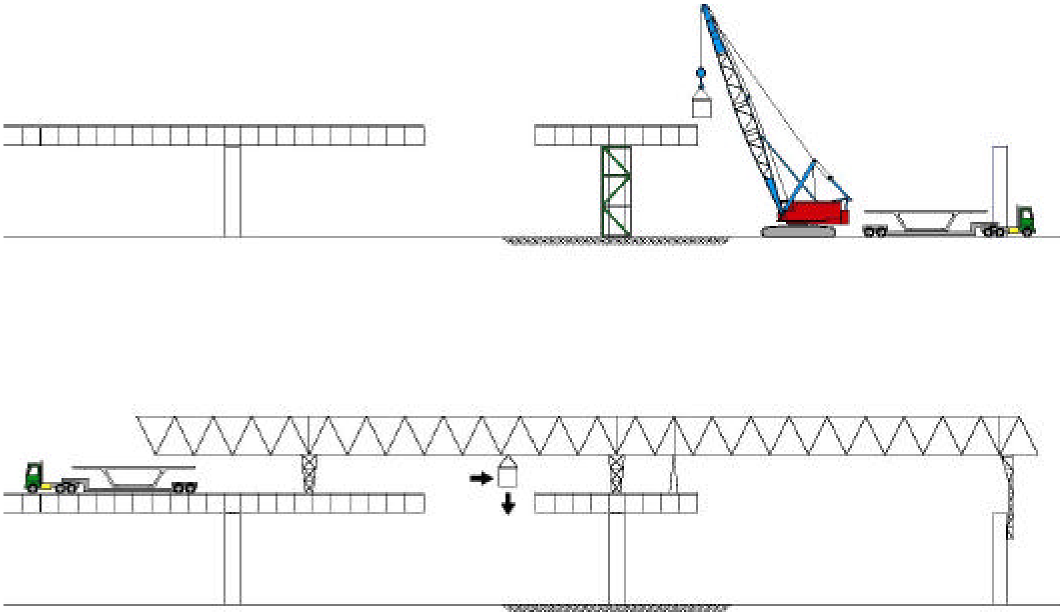


Figure 2.1 – Balanced Cantilever Construction

Once all of the segments of adjacent cantilevers are erected and tendons stressed, a closure joint is poured and continuity post-tensioning tendons stressed. These operations repeat until all spans of the bridge are assembled.

Figure 2.2 shows a perspective of a typical precast balanced cantilever segment with the various types of tendons that might be present. Each of the tendon types is described in following sections.

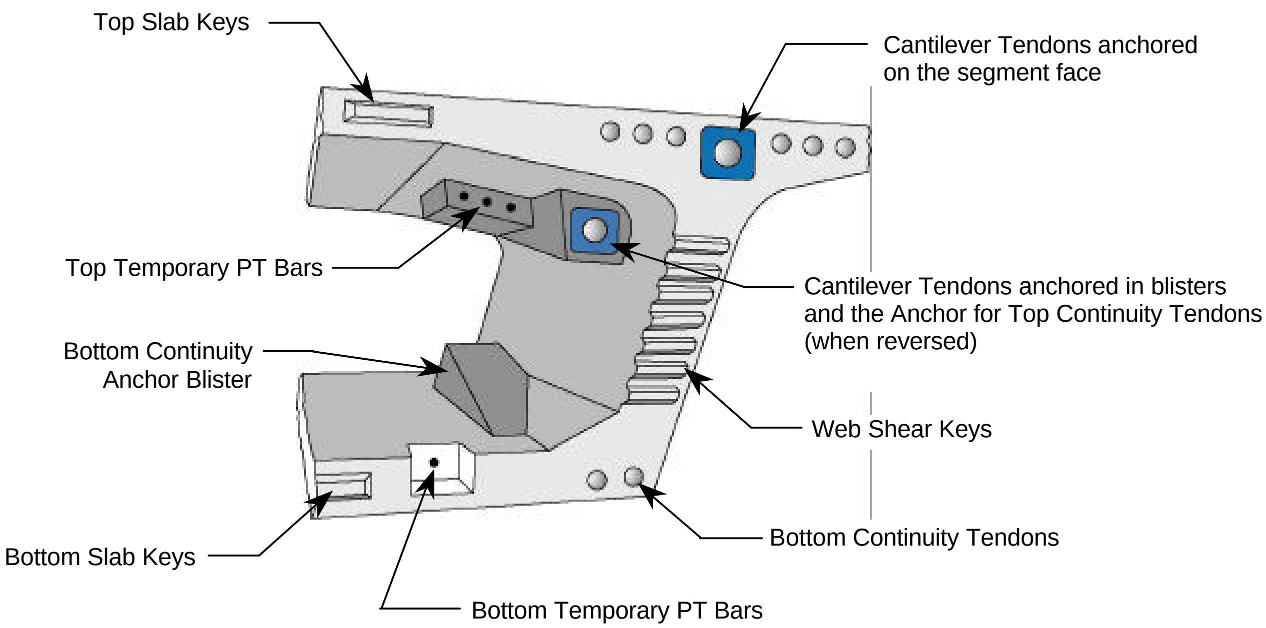


Figure 2.2 – Typical Balanced Cantilever Segment

2.1.1 Cantilever tendons

For cantilever erection, post-tensioning tendons are contained within the top slab of the segments and are usually placed in a single layer grouped over each web. Occasionally, when the span lengths warrant, there might be a second, lower layer of just a few tendons, with sufficient concrete thickness provided in the top slab. Cantilever tendons are typically placed in galvanized corrugated sheet metal ducts or corrugated polyethylene ducts. As tendons are anchored at each segment, the adjacent ducts are deviated laterally within the top slab to align with the anchor location. Therefore, all cantilever tendons can be anchored at the same relative position at each segment.

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

Figure 2.3 shows a typical layout for cantilever tendons that are anchored on the face of the precast segments. This detail, unfortunately, does not allow the later inspection of the anchor head following tendon grouting if additional segments are placed in cantilever after stressing. An alternate approach, shown in Figure 2.4, is to anchor the cantilever tendons in blisters cast with the segments at the intersection of the top slab and web. Anchorages of these tendons can be inspected at any time.

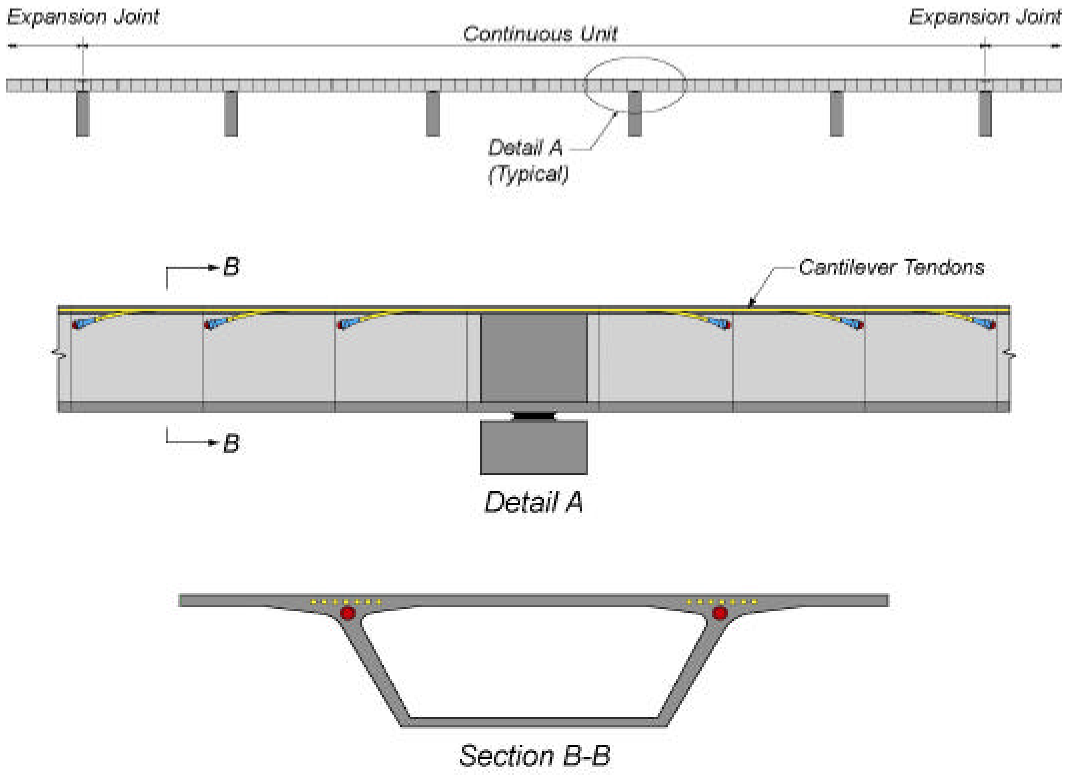


Figure 2.3 – Cantilever Post-Tensioning Tendons Anchored on the Segment Faces

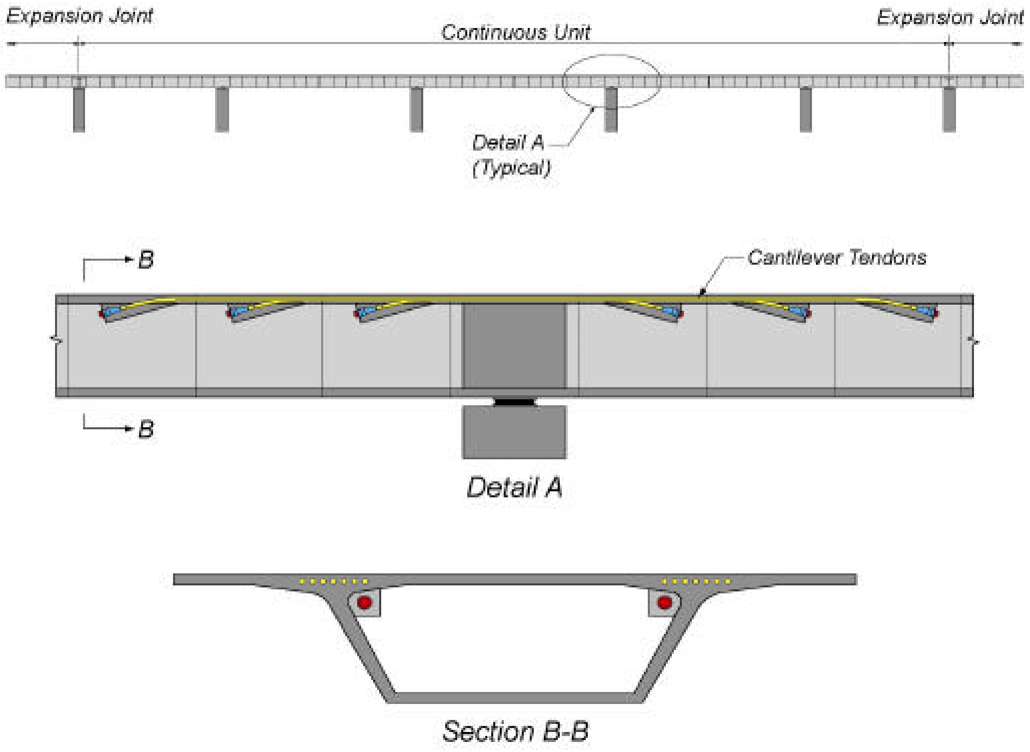


Figure 2.4 – Cantilever Post-Tensioning Tendons Anchored in Top Blisters

2.1.2 Continuity Tendons

To complete a span, the ends of two adjacent cantilevers are connected by a cast-in-place closure pour at or near mid-span of interior spans, but usually nearer to the end of end spans. The length of the closure (of the complete cross section of the superstructure box) may be a few inches to several feet. In order to align and hold the cantilever tips while making the closure, a special device, known as a *closure beam* or *strongback*, is fastened across the tips of the cantilevers. Formwork is secured around the closure, reinforcement and transverse post-tensioning is installed if required, and the closure concrete is poured. When the closure concrete attains sufficient strength, additional post-tensioning (continuity) tendons are installed, tensioned and grouted. Figure 2.5 depicts typical locations and layouts for bottom continuity tendons at mid-span.

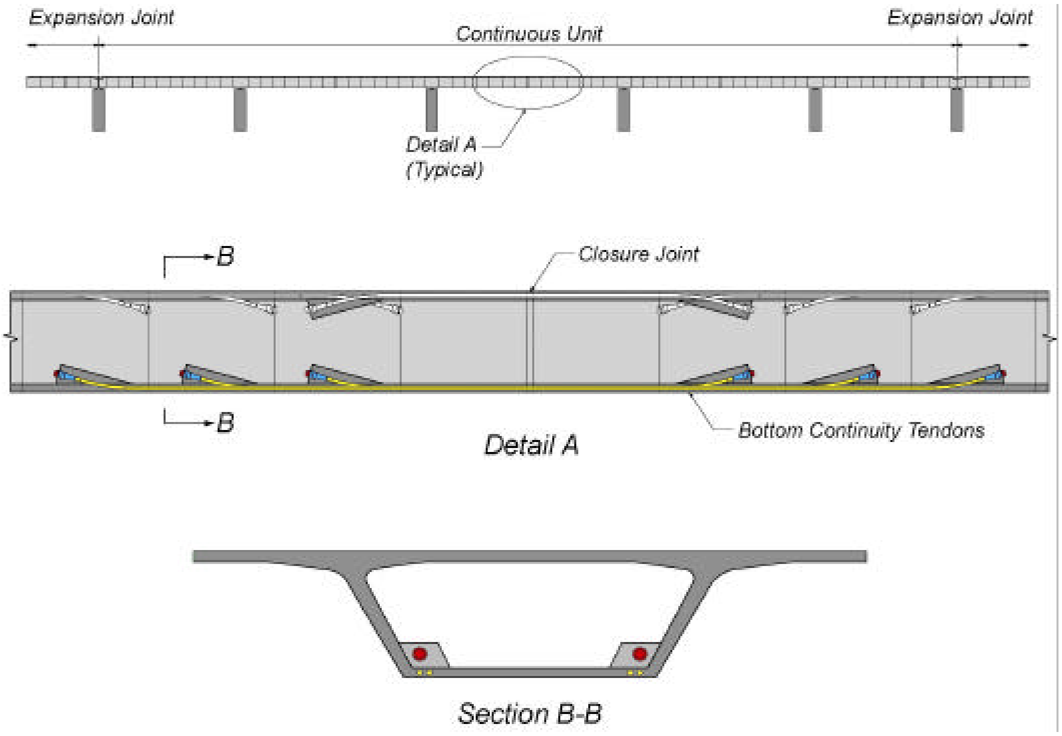


Figure 2.5 – Bottom Continuity Tendons for Balanced Cantilever Construction

When the closure is several feet long, and the closure segment weighs more than one half as much as a typical precast segment, it is necessary to pour the closure concrete in a very specific sequence in order to prevent the closure joints opening or cracking as the cantilevers deflect. Occasionally it is necessary to apply a small amount of post-tensioning (10% to 20% of two continuity tendons) through the closure just as soon as the bottom slab concrete has taken an initial set (i.e., within about 2 to 4 hours of casting). This will then keep the closure joints tight, even as the weight of more concrete is added to the closure.

Top continuity post-tensioning tendons are also typically required in balanced cantilever bridges.

A bridge built in cantilever will have no self-weight stress at the location of the closure joint in the center of the span. Midspan bottom continuity tendons produce tensile stresses in the top slab at the closure joint that need to be counteracted with top continuity tendons. Subsequent application of the barrier railing and possible wearing surface will produce top compression at this location and minimize the need for the top continuity tendons. However, live loads in adjacent spans could again produce a stress that would cause tension in the closure joint and again require the top continuity tendons. Ultimately, redistribution due to the creep of the concrete will induce compression in the top, again reducing the need for top continuity tendons. Figure 2.6 shows details of the top continuity tendons.

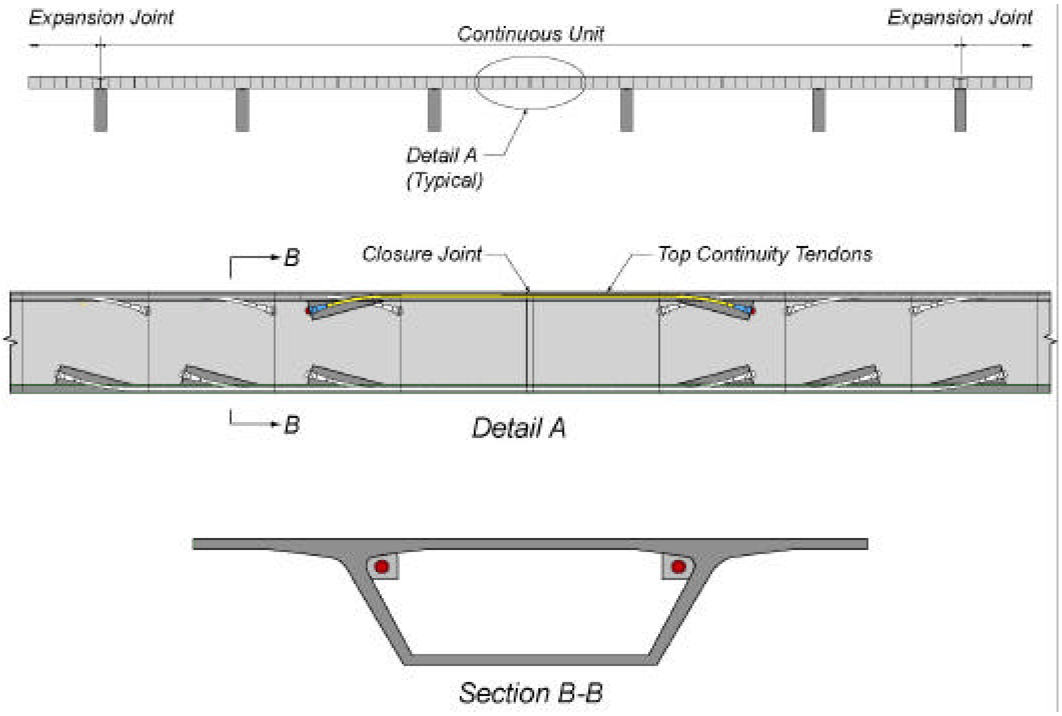


Figure 2.6 – Top Continuity Tendons for Balanced Cantilever Construction

2.1.3 Continuity Tendons At Expansion Joints

Typically, several segments constructed on falsework are needed to complete expansion joint spans that terminate at expansion joints (at abutments and expansion piers). Figure 2.7 shows a typical detail for segment construction at these locations. A closure joint is made next to the cantilever in the same way as for an interior span closure between two cantilevers. Continuity post-tensioning tendons are installed in both the top and bottom, extending from the expansion joint segment in to the cantilever. Typically there are more continuity tendons in the bottom than the top, and occasionally no continuity tendons may be needed in the top at all. It is considered good practice, however, to provide at least two, one over each web, in the top. End span continuity tendons may be stressed from the expansion joint segment if access is available. Alternatively, they may be stressed from within the superstructure itself at anchor blisters.

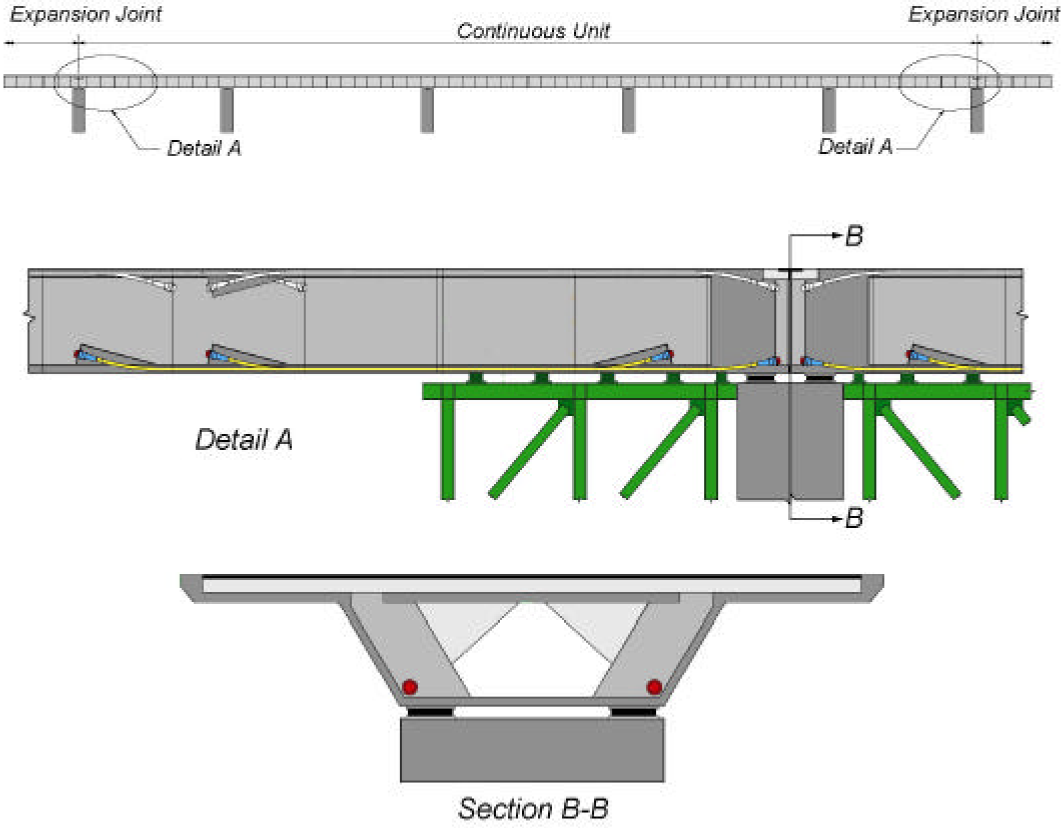


Figure 2.7 – Bottom Continuity Tendons Near an Expansion Joint Over a Support

A few balanced cantilever bridges built earlier in Florida's history accommodated expansion and contraction by placing expansion joints at the quarter points of the expansion joint spans (Figure 2.8). These joints were placed here because the alternative of a hinge at midspan had been ruled out by policy of the Federal Highway Administration following a few cases of unpredicted excessive midspan deflection on a few bridges in Europe and the United States. Unfortunately, quarter point hinges proved less than successful and exhibited complex crack patterns in the dapped hinge zones and the diaphragms adjacent to the hinges. External vertical and longitudinal post-tensioning were added to strengthen these bridges in the vicinity of the hinge.

Revisions to long-term deflection models of concrete have reduced deflection uncertainties and midspan hinges have again been used satisfactorily. Deflection control is further assured by placing steel beams on sliding bearings inside the box girder, between the cantilevers so that they allow for expansion and contraction, but control rotation of the hinge.

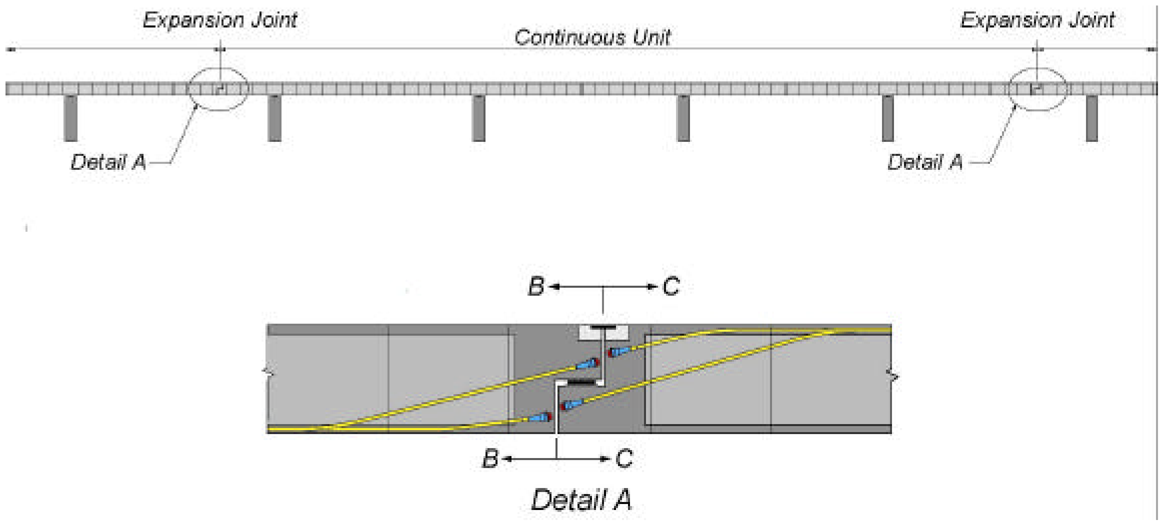


Figure 2.8 – Quarter Point Hinges in Balanced Cantilever Construction

Difficulties with the quarter-point detail in balanced cantilever construction led to another construction approach to providing expansion joints in long structures of long span lengths. This method calls for placing expansion joints over the piers and temporarily stressing the expansion joint segments together to form a single pier segment. The segments on either side of the expansion joint are then placed in cantilever until the adjacent mid-spans are reached. Once closure joints are poured and continuity tendons stressed, the cantilever tendons through the expansion joint segments are removed and the two expansion joint segments separated from each other to allow the necessary thermal and long-term movements. This method of construction was used at the Roosevelt Bridge in Martin County.

2.2 Precast Segmental Span-by-Span Bridges

Span-by-span construction calls for the erection of all segments of a span on a temporary support system with small closure joints cast adjacent to the pier segments, then full span tendons are installed and stressed. The tendons must drape between piers, being anchored near the top of the section at the piers and deviated to the bottom of the section within the mid-span region. In order to achieve continuity with the next span, the tendons from one span overlap with the tendons of the next in the top of the pier segment common to each span. At the very ends of each continuous unit, the ends of the tendons anchor in the diaphragm of the expansion joint segment with anchors arranged approximately parallel to the web of the box. Figure 2.9 shows typical phases for span-by-span construction.

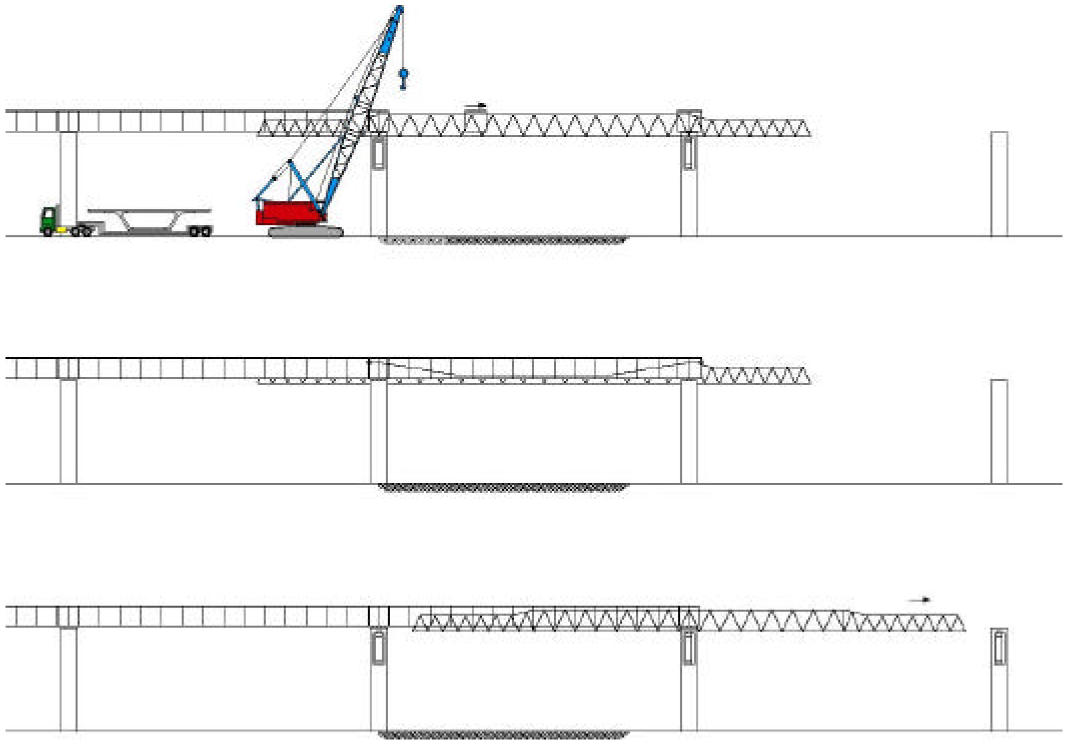


Figure 2.9 – Span-By-Span Construction

In the first span-by-span bridges in the Florida Keys, and in many similar bridges since, the tendons are external to the concrete. Structurally, with no tendons in the webs, the cross section of the box is optimized for both longitudinal and transverse efficiency, in particular using a web thicker at the top than bottom. This also raises the centroid of the whole cross section, maximizing the eccentricity and efficiency of the post-tensioning in the mid-span region needed for the dominant longitudinal bending of span-by-span erection. Figure 2.10 shows a typical layout of span-by-span tendons for an interior span where all tendons deviate at a common deviation saddle. Figure 2.11 shows a similar layout for a typical expansion joint span. Current designs may have an additional straight tendon per web, per span to control the effects of thermal gradient.

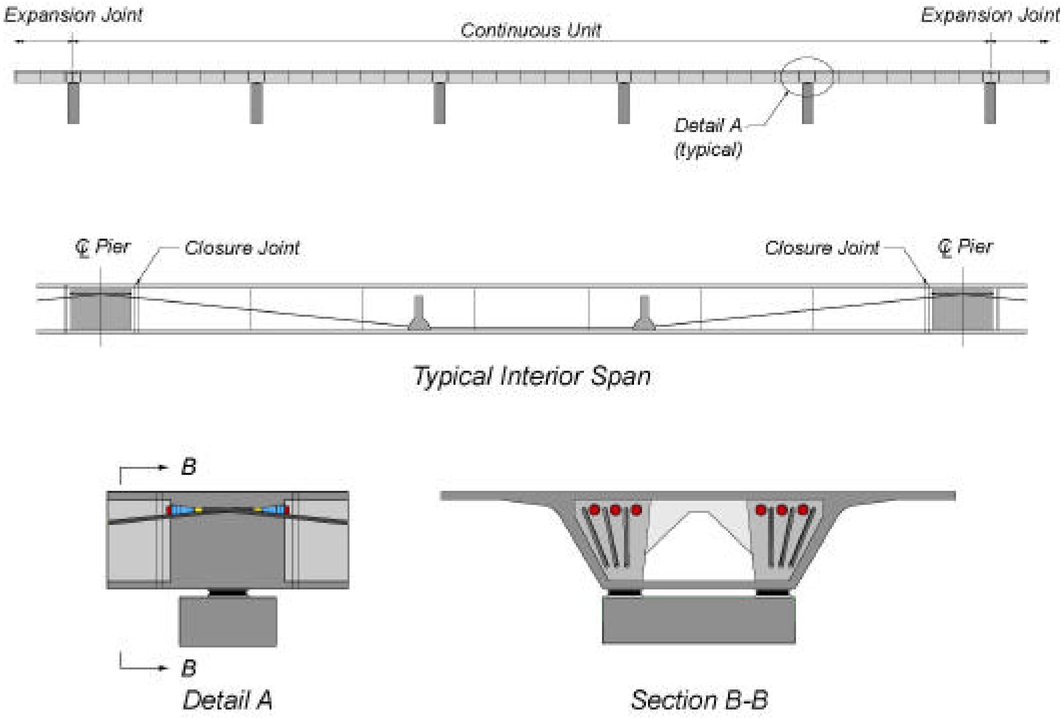


Figure 2.10 – Interior Span Post-Tensioning for Span-By-Span Construction

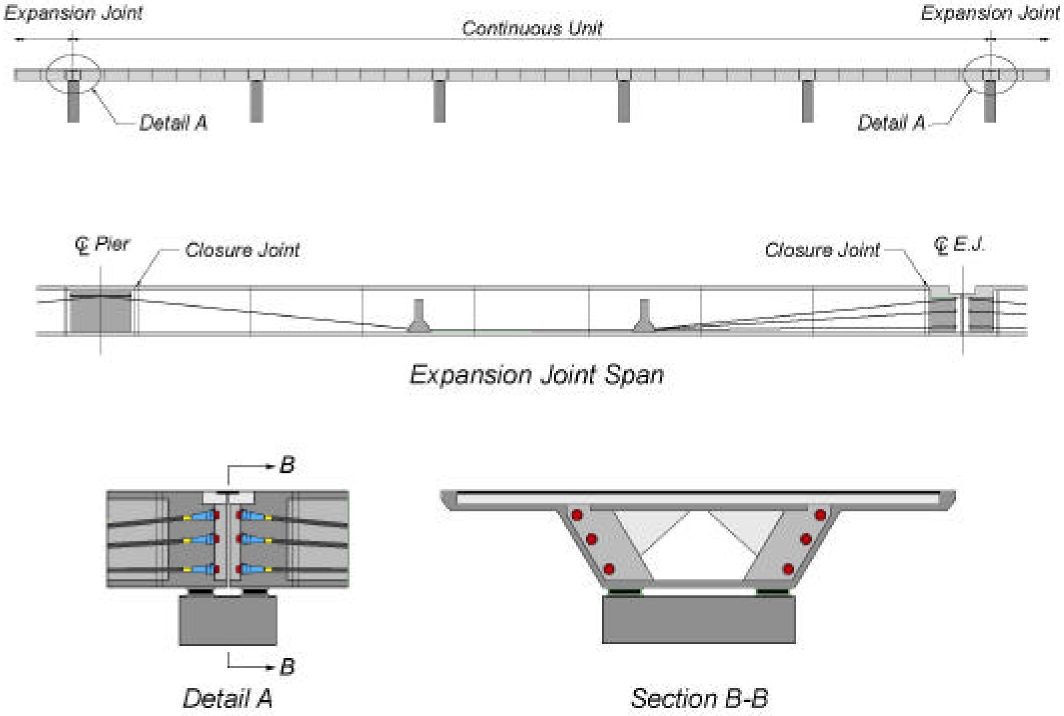
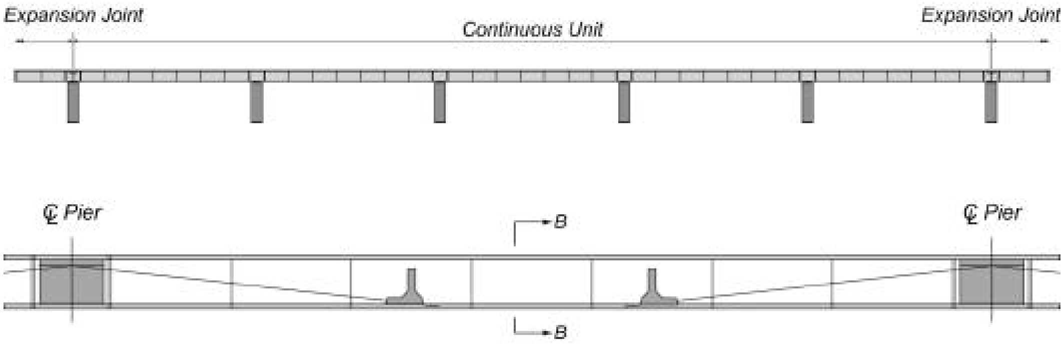


Figure 2.11 – Expansion Joint Span Post-Tensioning for Span-By-Span Construction

Each post-tensioning tendon of the Evans Crary Bridge in Stuart, Florida is both external and internal to the concrete. The profile of the post tensioning tendons is similar to that of external tendons except for the fact that between the deviation diaphragms, the tendons enter and pass through the bottom slab. The tendons are external in the inclined regions. Figure 2.12 shows the layout of these tendons. This layout provides for additional eccentricity of the tendons at midspan, but does not allow for visual inspection of the external tendons where they pass through the bottom slab, or for future tendon replacement.



Typical Interior Span

Section B-B

Figure 2.12 – External/Internal tendons of the Evans Crary Bridge

2.3 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 transport and erection. The girders are erected as simple spans between piers and cast-in-place joints that are a part of transverse diaphragms are poured. Longitudinal post-tensioning tendons are threaded through ducts already cast into the webs and stressed, establishing continuous behavior.

The simplest form of a continuous, post-tensioned AASHTO or bulb-T girder bridge has ducts that follow a smoothly curved, draped profile running continuously through multiple beams in line and are spliced at the cast-in-place joints at the beam ends. Tendons rise to the top of the girder over the interior piers of a typical unit and drape in the web into the bottom flange of the girder in the mid-span regions. Tendons can be anchored in a variety of configurations at the ends of each continuous unit. Early designs in Florida called for all tendons to rise up to the top flange and anchor in a series of block-outs formed in the top of the bulb-tee girder. Subsequent designs have used wider end blocks to accommodate a variety of anchor locations.

The construction sequence begins by erecting simple span girders on their bearings at the piers. Tendon ducts are then spliced and closure joints are poured at the interior piers and a first stage of post-tensioning is stressed, making the girders continuous. Next the slab is cast and allowed to cure. The unit is complete when a second stage longitudinal post-tensioning is applied to the composite section.

Details of the longitudinal tendons at end of the girders and over the piers for the Eau Gallie Bridge are shown in Figure 2.13. For this project the tendons actually rose out of the beams and into the top slab over the piers. In a construction change proposed by the Contractor, the originally designed four tendons of 9, 0.6-inch diameter strands per beam were changed to three tendons of 12, 0.6 inch diameter strands. Since the original bulb-T had a web only 6 inches thick, it was difficult to accommodate the ducts, rebar and cover. Similar difficulties arose after a few similar applications using oval ducts with a 7-inch web width and increased side cover. Currently, most designs increase the web thickness to 8 inches. The Florida bulb-T, with minor modifications and improvements, has been used successfully on many long and major bridges.

Anchors at Beam End

Rising Ducts at Piers

Figure 2.13 – Eau Gallie Bridge Continuity Tendon Layouts

Larger channel crossing spans can be built effectively using similar techniques. Rather than placing simply supported beams and then making them continuous, a variable depth girder section cantilevering over a pier may be spliced to a typical bulb-tee girder in the main and side-spans.

Figure 2.14 shows four photographs of the construction of a three span main unit for the Flagler Beach Boulevard Bridge. Temporary supports are erected at the splice location in the side spans (upper left). The end of the girders have protruding mild reinforcing bars that will be help secure the girder to the closure and ducts that splice with those of other girder sections allowing for placement of tendons over the full length of the main unit (upper right). The variable depth girder sections are placed over the piers, aligned with the girders of the side spans, and closures cast (lower left). Temporary strongback beams support the drop-in girder of the main span while closures are cast (lower right). When all closures have reached sufficient strength, the longitudinal post-tensioning tendons are placed and stressed. Phased stressing on the non-composite and composite sections may be used to maximize the efficiency of the post-tensioning.

Figure 2.14 – Spliced Girder Main Unit of the Flagler Beach Boulevard Bridge

2.4 Cast-in-Place Segmental Balanced Cantilever Bridges

The three span main structure of the Acosta Bridge in Jacksonville, Florida is the State's only cast-in-place balanced cantilever bridge. The longitudinal post-tensioning of this structure is comprised of cantilever tendons in the top slab, continuity tendons in both top and bottom slabs through the mid-span closures, similar to precast cantilever bridges previously described. Unlike precast segmental construction, no temporary longitudinal post-tensioning bars are needed for erection of the cast-in-place cantilevers. The form travelers support the concrete until it has reached a satisfactory strength for post-tensioning. The Acosta Bridge has permanent vertical post-tensioning bars used in the deep web segments to help control shear stresses.

2.5 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. Forms are used to create the shape of the concrete section and any internal voids or diaphragms. All reinforcement and ducts for post-tensioning are installed in the forms and then the concrete is poured, consolidated and cured. When the concrete attains sufficient strength, post-tensioning is installed and stressed to the required forces.

Longitudinal post-tensioning usually comprises multi-strand tendons smoothly draped to a specific vertical profile. In continuous spans, the tendon profile drapes to the bottom of the section in the mid-span region and rises to the top of the section over interior supports. In simple spans and at the expansion ends of continuous spans, the 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 prestressing.

2.6 Temporary Longitudinal Post-Tensioning (Bars)

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

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

Temporary post-tensioning bars were not used for span-by-span erection with dry-joints (AASHTO Type B joints). However, temporary PT bars are usually needed for span-by-span erection with epoxy joints 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 single span at one time.

2.7 Transverse Post-Tensioning of Superstructures

2.7.1 Transverse Top Slab Post-Tensioning

Box Girder Superstructures

The top slabs of the first segmental superstructure boxes in the Florida Keys (Long Key, Niles, Channel Five) were transversely pre-tensioned – Seven Mile was only reinforced with epoxy-coated rebar. All subsequent top slabs in precast and cast-in-place segments have been post-tensioned with transverse, internal, multi-strand tendons grouted after stressing. Tendons are spaced at intervals, typically 2 to 3 feet, along the structure. Tendons typically anchor in the edges of the top slabs in cantilever wings in blockouts. The blockouts are subsequently filled with concrete and usually covered with a traffic barrier. Figure 2.15 shows a perspective view of typical transverse post-tensioning tendons in a box girder.

Wide bridges are often made of twin parallel box girder bridges joined by a longitudinal cast-in-place concrete strip. The cast-in-place closure strip can be conventionally reinforced or transversely post-tensioned. When post-tensioning is used, a few transverse tendons are typically stressed in the individual segments to allow for the shipment and erection of the individual segments. Other tendons are then placed through ducts in adjacent segments and the closure strip and stressed across the full width of the bridge.

All top slab transverse tendons are tensioned and grouted – usually while the segment is in storage in the casting yard.

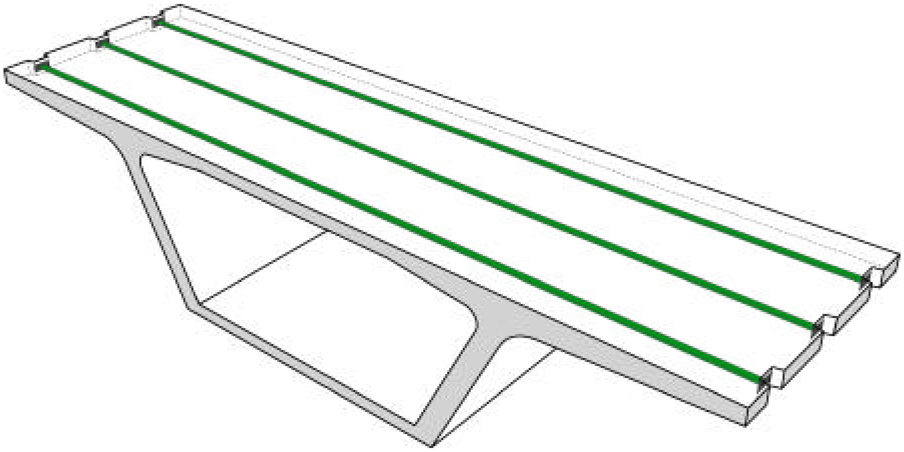


Figure 2.15 – Transverse Post-Tensioning in the Top Slab of Precast Box Girders

Multiple Precast Element Superstructures

There are several short span bridge types used in Florida that are comprised of multiple precast, prestressed elements placed adjacent to one another to form the bridge superstructures. Some of the precast elements used to form these bridges include flat slabs, double-tees, inverted-tees, and box beams. These bridges can be built with or without toppings. The precast elements are connected transversely with longitudinal closure pours and transverse post-tensioning. High strength bars, mono-strands or multi-strand tendons can be used for transverse post-tensioning. The amount of post-tensioning is a function of the specific bridge design requirements.

2.7.2. Transverse Post-Tensioning in Diaphragms

Superstructure pier segments are occasionally transversely post-tensioned with multi-strand tendons. These tendons may crisscross, draping from the wing on one side to the opposite face of the web on the other (i.e. at I-75/I-595 and US441/I595 interchanges and Sunshine Skyway) otherwise the transverse post-tensioning extends from web-face to web-face (Figure 2.16). These tendons are internal tendons in metal ducts and are stressed and grouted in the casting yard.

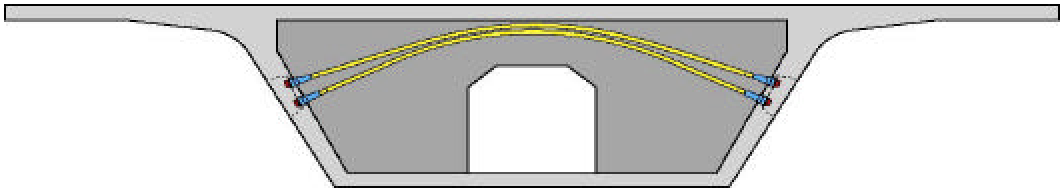


Figure 2.16 – Transverse Post-Tensioning in Diaphragms

2.7.3 Vertical Post-Tensioning in Diaphragms

Vertical post-tensioning bars (Figure 2.17) 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. They are internal tendons in metal ducts and are stressed and grouted in the casting yard.

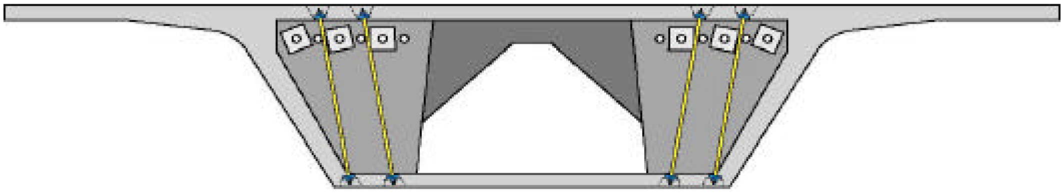


Figure 2.17 – Vertical Post-Tensioning in Diaphragms

2.7.4 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 faces (e.g. Mid-Bay and Garcon Point and the side spans of the Sunshine Skyway Main Structure). Figure 2.18 shows a typical layout for these transverse post-tensioning bars. The bars are stressed and grouted in the casting yard.

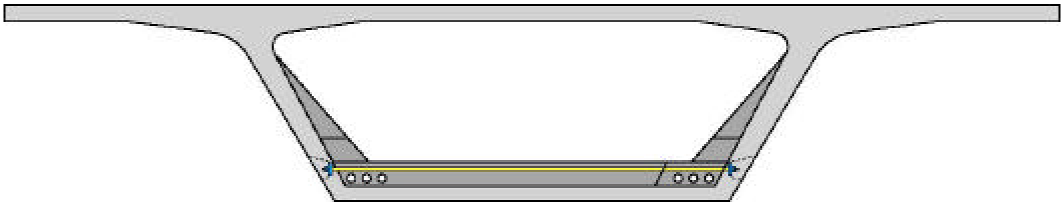


Figure 2.18 – Transverse Post-Tensioning in Deviation Ribs

2.7.5 Vertical Post-Tensioning Bars in Webs

Vertical post-tensioning bars are occasionally added to webs, usually in the high shear zone near the piers, to control principal tension stresses and mitigate or avoid associated cracking. For example, vertical PT bars were provided in shear zones of the webs of the Acosta Bridge. Figure 2.19 shows typical vertical post-tensioning bars in the webs of an inclined web box girder.

Web post-tensioning in the form of strand tendons are used in the main structure of the Sunshine Skyway Bridge. Web tendons anchor at the base of the highly inclined webs and curve into the cantilever wings of the segments where they are anchored at the segment extremities. The top slabs of the 95-foot 7-inch wide segments are supported by a system of internal struts. At stay anchor locations these struts are in tension and inclined post-tensioning tendons are used to maintain compression in the struts and thereby transfer the vertical component of the stay force to the bottom of the webs.

Figure 2.19 – Vertical Post-Tensioning in Webs

2.8 Post-Tensioning of Substructures

In Florida, most substructures for standard AASHTO type I-girders, Bulb-T's, spliced girders, cast-in-place post-tensioned and many segmental structures are of ordinary reinforced concrete construction. However, for larger bridges and special situations, post-tensioning finds application. The most usual applications are as follows.

2.8.1 Hammerhead Piers

Transverse post-tensioned tendons using strand or bar tensile elements provide an effective reinforcing scheme for Hammerhead Piers (Figure 2.20). 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.

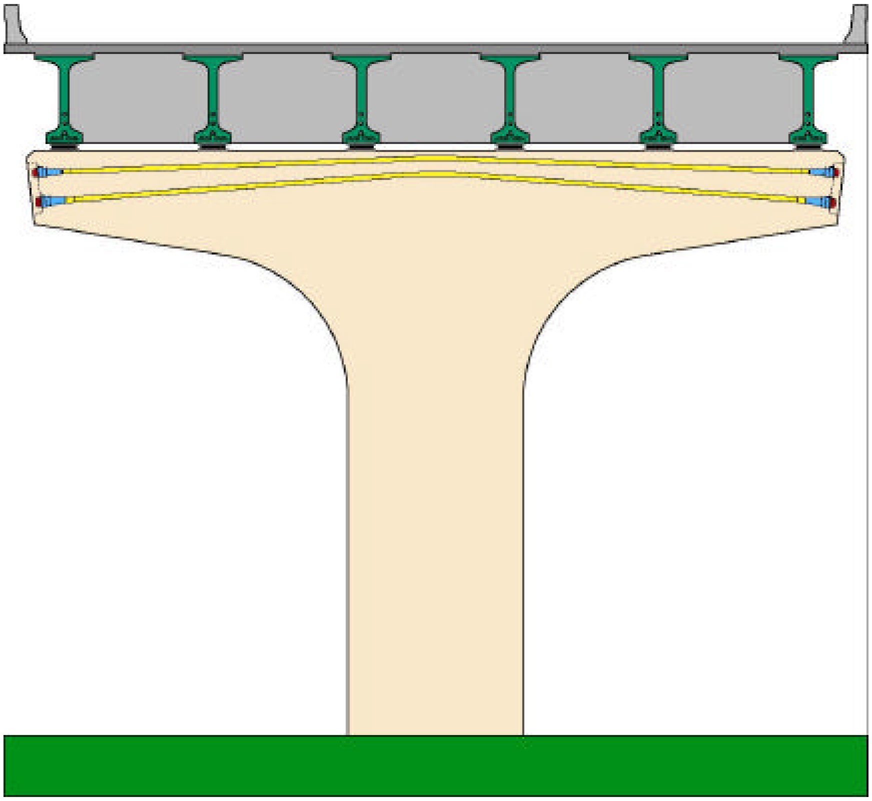


Figure 2.20 – Post-Tensioning in Hammerhead Piers

2.8.2 Straddle Bents

Straddle bents are often required to support upper level roadways in complex multi-level interchanges (Figure 2.21). 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.

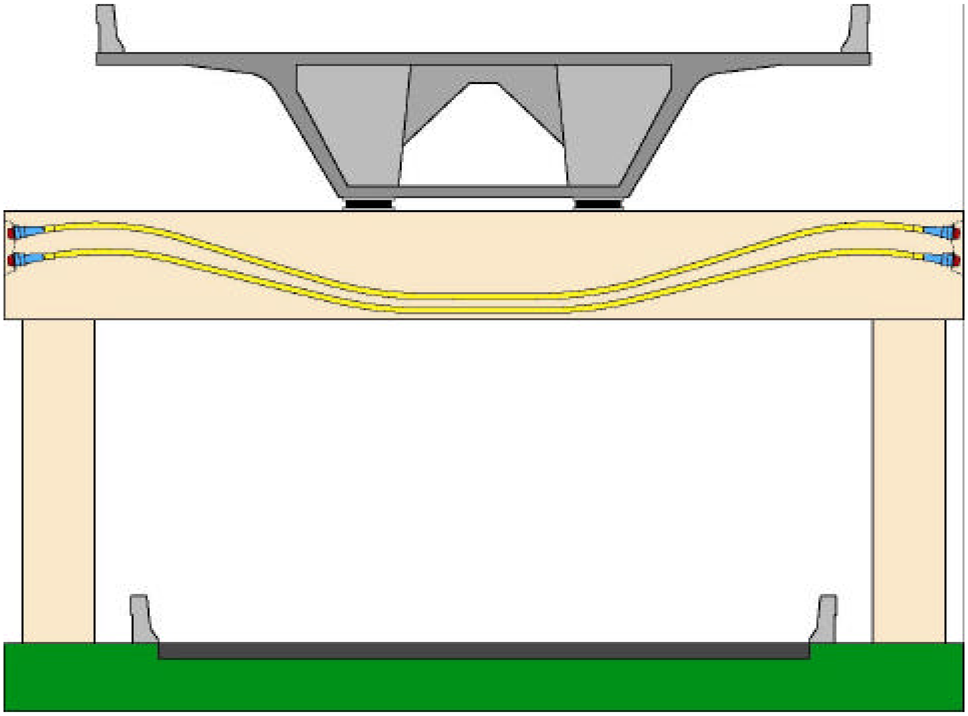


Figure 2.21 – Post-Tensioning in Straddle Bents

2.8.3 Cantilever Piers

Cantilever piers (C-piers) are often used in multi-level interchanges or in flyover bridges where a concentric column would intrude into a horizontal clearance associated with an underlying roadway. For structural efficiency and economy, a typical cantilever pier usually contains transverse and vertical post-tensioning (Figure 2.22) rather than solely being reinforced.

Correct detailing of cantilever piers provides 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 could be used for repair or rehabilitation: however, special attention would be needed to anchor them and develop forces around the top corner and into the footing.

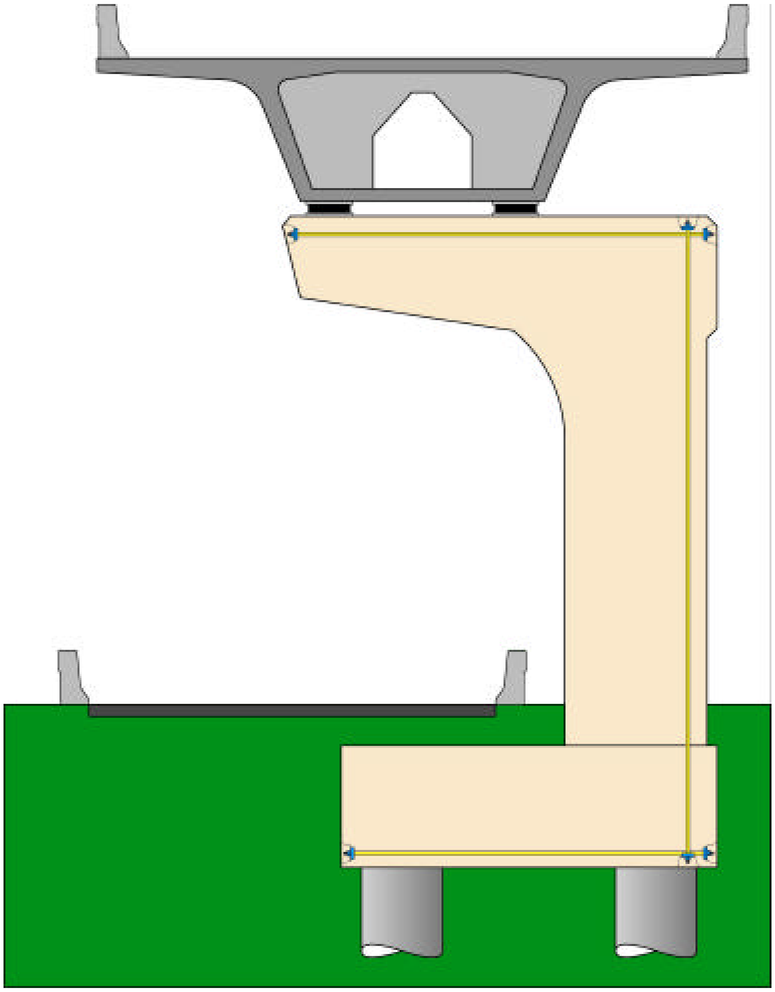


Figure 2.22 – Post-Tensioning in Cantilever Piers

2.8.4 Precast Box Piers

Hollow rectangular section, precast concrete segmental piers were first used for the high level portions of Seven Mile and Channel Five bridges in the Florida Keys. These sections match the full width of the bottom soffit in the transverse direction and are 8 feet in the longitudinal direction. Vertical post-tensioning consisted of post-tensioning bars in each corner of the box piers (heights up to 65 feet).

Similar, but much taller, hollow oval section piers are used for the high level approaches to the Sunshine Skyway Bridge. The height and slenderness requires more prestress – in this case applied by vertical tendons containing as many as 17 strands of 0.5-inch diameter. Most tendons anchor in the pier caps, some anchor partway up on the interior portion of the pier where the wall steps to a greater thickness (Figure 2.23). Smooth plastic duct was used as the primary duct in the precast segments of the piers. When the wall thickness increased these smooth plastic ducts were placed inside of corrugated plastic ducts that were cast into the segments. All of the vertical tendons loop through the foundations in pre-formed steel pipes.

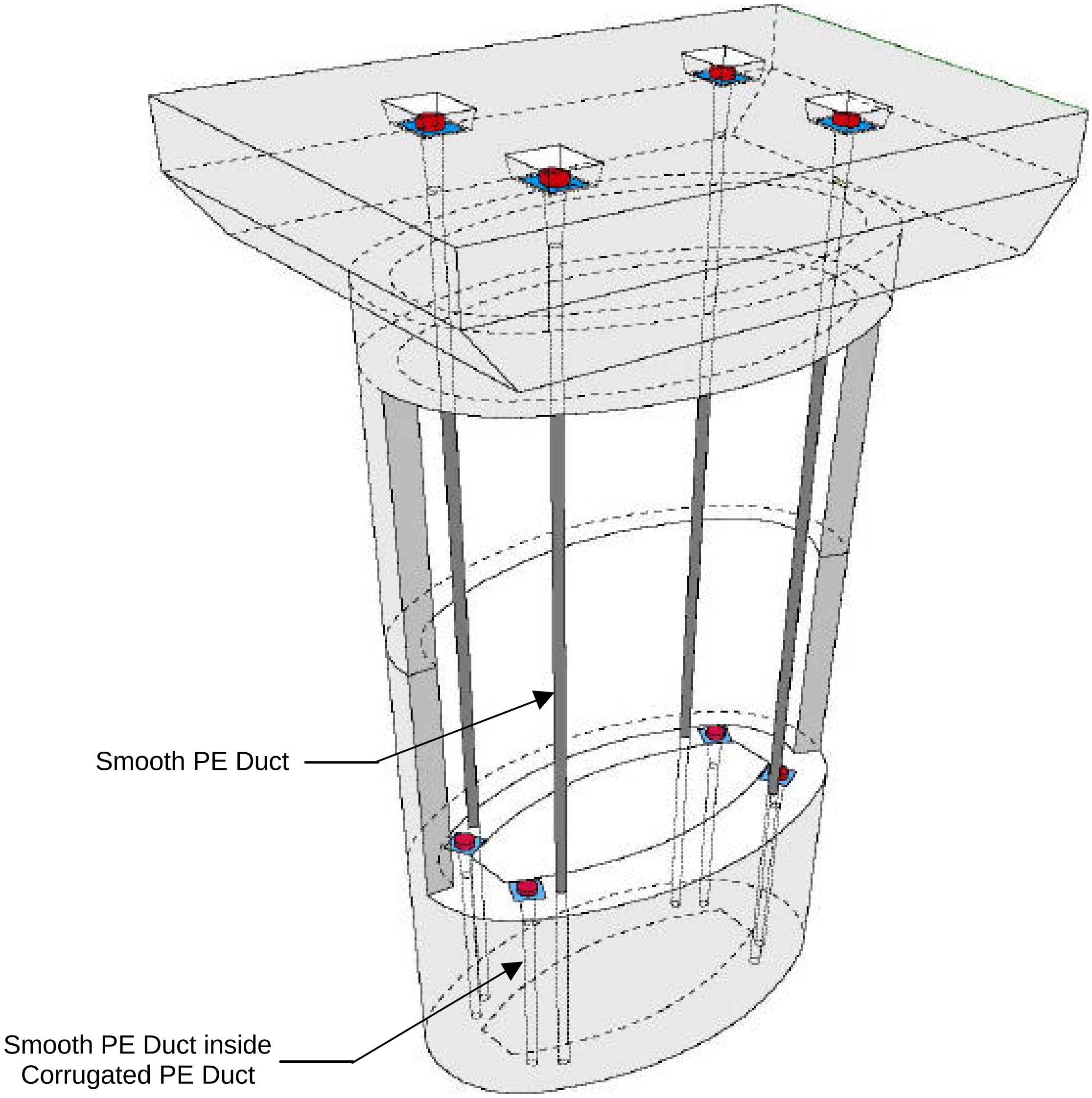


Figure 2.23 – Vertical Post-Tensioning of the High Level Approach Piers of the Sunshine Skyway Bridge

2.8.5 Precast I-Section Pier Columns

Precast segmental I-section piers are used for the Mid-Bay Bridge. These are post-tensioned with strand tendons, looping through the foundations. A connector is located at the base of the column at the top of the footing on the four inside faces of the legs of the I-section.

Precast I-section piers are also used at the Edison Bridge in Fort Myers - a bulb-T girder bridge.

The pier columns are connected to the foundation using a special large diameter rebar splice-coupler also located at the base of the column at the top of the footing.

2.8.6 Transverse, Confinement Tendons at Tops of Piers

Large concentrated bearing loads on the top of piers induce local transverse tensile stress. This may be resisted by mild steel reinforcement or by transverse post-tensioning. For example, the tops of the large elliptical section piers of the main span unit of Sunshine Skyway Bridge (1987) are confined by horizontal, internal multi-strand transverse tendons laid to hoop around the edges. The pier tops for the approach piers for the 17th Street Causeway Bridge in Fort Lauderdale have transverse PT bars.

Chapter 3 – Critical Nature of Tendons

3.1 Introduction

All post-tensioning tendons are important. They are installed for a purpose – to provide the necessary prestress forces to counter the effects of permanent and traffic loads. However, when comparing the relative durability of different post-tensioned bridge types, or when planning the effective deployment of inspection and maintenance resources it may be beneficial to identify a hierarchy of the types of post-tensioning tendons used in Florida.

In developing this hierarchy, or relative importance of tendons, it is important to consider the wide range of influencing factors. For example, some tendons are provided to facilitate a particular type of construction or carry construction loads that may be greater than the final structural condition. As a result, their relative importance in the completed bridge may not be as critical as other more significant tendons.

Structural configuration also bears on the relative importance of tendons. Continuous structures are redundant and are capable of redistributing forces internally at post-elastic load levels, creating mechanism in which certain tendons may be more significant in providing resistance than others. Continuous post-tensioned structures with multiple girder lines provide additional levels of redundancy, further affecting the relative importance of tendons.

The corrosion protection system provided by a particular bridge type has an impact on the resulting relative importance of the tendons in that bridge. It may be more important to review the condition of tendons of a precast segmental balanced cantilever bridge more so than the same bridge built with cast-in-place balanced cantilever construction. In the second method of construction the ducts are easily made continuous and duct splices can be offset from construction joints and buried in subsequent concrete pours.

This Chapter attempts to establish a hierarchy for the types of tendons used in Florida bridges. This hierarchy is a relative measure only and for comparative purposes is establishing inspection and maintenance priorities. It is not intended to down play the importance of any tendon with regard to its specific structural purpose in a particular bridge.

3.1.1 Influence of Type of Construction

When, for example, a segmental superstructure is built in balanced cantilever, the maximum load is often that from the weight of the cantilever itself and other loads during construction. Consequently, cantilever post-tensioning is usually conservative and more than sufficient to sustain the self-weight alone. Under long-term service conditions, redistribution of internal forces from dead load (self weight etc.) and prestress occurs. Along with live loads, the redistribution of internal forces necessitates continuity tendons to connect cantilevers and end span portions. After installation, these induce further internal force redistribution making the final internal state of stress complex but redundant.

Subsequent removal or loss of a continuity tendon (say through corrosion) would make the structure revert toward acting in the manner it was built. In the case of balanced cantilever construction, this would mean relying more on the cantilever tendons. On the other hand, removal or loss of a cantilever tendon would induce different internal force redistribution placing greater reliance on the mid-span continuity tendons. In general, a continuous cantilever structure has significant ability to redistribute internal forces - taking advantage of its structural redundancy and large number of negative moment tendons over the pier.

In similar fashion, the corrosion of a longitudinal post-tensioning tendon in a continuous bulb-tee girder bridge could cause the girder to move toward the simple span condition under which it was erected. As the girder attempted to behave in this fashion the benefits of lateral redundancy would appear, carrying load to adjacent girders through the deck slab.

Similar considerations apply to other types of post-tensioned construction, structures cast-in-place and post-tensioned falsework and to spliced I-girder methods of construction.

3.1.2 Influence of Tendon Bond

Although tendons are initially tensioned and anchored at their ends, grouted internal tendons can develop bond to the concrete through the grout along their length. So, if corrosion of strands occurs in the anchor, capacity of the entire tendon is not lost and may remain sufficient at critical sections. External tendons are anchored at their ends and develop little or no bond in the length through a diaphragm or deviator. Corrosion of these tendons can lead to dramatic failures.

3.1.3 Influence of Tendon Protection System

The main tensile elements of post-tensioning tendons in existing Florida bridges are typically protected against corrosion by a combination of concrete cover, ducts, and grout. The extent to which these three function effectively depends on the quality of the individual materials, workmanship, inspection during construction, and the type of construction as well.

Concrete Cover

Tendons of cast-in-place concrete bridges with infrequent, or no construction joints provide a near ideal barrier to free water and contaminants. When the concrete properties are enhanced by use of fly ash, micro-silica and similar admixtures that act to slow migration of chloride ions, or when the concrete is coated with penetrating sealants, the protection of the tendons is further improved. Bridges with more frequently occurring construction joints, such as cast-in-place balanced cantilever bridges, could provide access for water and contaminants to the post-tensioning. Continuity of mild reinforcing across the construction joints helps to maintain the corrosion protection provided by concrete cover.

Bridges built using precast segmental methods introduce joints that interrupt the protection offered by the concrete cover. Therefore, these joints need to be properly sealed with epoxy during construction. Breach of the seal can allow contaminants to enter and attack tendons.

External tendons receive corrosion protection from embedment in the superstructure concrete only at diaphragms and deviators. In other locations, these tendons are outside of the concrete but inside the interior of box girders, with protection principally supplied by duct and grout alone.

Ducts

Different types of ducts offer varying degrees of corrosion protection. Helical wound, galvanized steel ducts do not provide a physical barrier to the migration of chloride ions through the concrete and grout. However, they offer sacrificial protection of the galvanized coating. Plastic ducts provide a physical barrier to the migration of corrosive elements, but they can suffer local damage or breach as strands rub against the duct wall during installation and stressing.

As originally used, ducts in cast-in-place post-tensioned bridges were never integral to the corrosion protection system. Their purpose was to create the hole through which the tendons would pass. The porosity of helical wound duct often used in cast-in-place construction was seen in early research by CALTRANS as an advantage, permitting the migration of excess water in grout that could then be absorbed by the surrounding concrete. In addition, the galvanizing offered a degree of sacrificial protection.

Ducts play a significantly different role with regard to external tendons. These ducts are made of solid extruded, high-density polyethylene and are connected to embedded steel pipes at diaphragms and deviators by elastomeric boots and clamps. All water introduced into the duct through the grouting process is either consumed in the hydration of the grout, bleeds through the anchor heads, or is locked inside the tendon. The hydrostatic head caused by the weight of the grout in a vertically deviated tendon can force excess water in to the interstitial areas between the individual wires of the post-tensioning strands and aggravate bleed conditions. In the free length of external tendons any imperfections in the grout can leave the polyethylene duct as the only defense against corrosion. This is especially true at the ends of the free lengths of deviated external tendons where the strands are not concentric with the duct but are grouped to one side and bear directly on inside of the duct.

Grout

Cement grout is chemically basic and provides a passive environment around the strands. In cast-in-place construction, where concrete cover offers the majority of the anticipated corrosion protection, the grout primarily serves to bond the tendon to the structure. In segmental structures with tendons passing through the joints, the concrete and duct are interrupted and the grout and epoxy at the joint provides the corrosion protection. In the free lengths of external tendons the principal role of the grout is to provide a chemically base environment inside the polyethylene duct.

After proper consideration for protection offered by concrete cover, ducts and grout, it is important to evaluate the protection of the tendon system as a whole. 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. Voids in anchors not tightly sealed can be recharged with humid air occasionally laden with salts. As temperatures change the humid air can condense inside the anchor and aggravate corrosion.

3.1.4 Influence of Maintainability - Accessibility and Inspectability

Accessibility to inspect, maintain, and if necessary, replace a tendon enters into the hierarchy for maintenance. Buried anchors of internal bonded tendons are not easy to access and inspect – destructive intrusion may be needed to examine such an anchor. On the other hand, anchors for external tendons are usually directly accessible, requiring only the removal of a local concrete pour-back to access the anchor head itself – likewise for tendons anchored in blisters.

3.1.5 Influence of Redundancy

Redundancy provides a measure of confidence that a structure will exhibit noticeable warning (such as excessive deflection or local cracking) without failure even when some internal parts may have failed locally (due to corrosion or other reasons) – thus affording time and opportunity for routine inspection to notice potential problems and take the necessary corrective action.

Most modern post-tensioned superstructures are made structurally continuous over one or more interior piers, providing longitudinal redundancy. In I-girder bridges, multiple (more than two) lines of girders provide lateral redundancy through multiple load paths. Hollow box section (segmental and similar) superstructures develop redundancy through their high torsion capacity and behavior that distributes loads around the section and along to different spans.

In addition to overall structural redundancy, there is sometimes benefit from having several small capacity tendons, rather than a few large capacity tendons, through a structure. In the event that one is lost due to corrosion, it represents a smaller proportion of the whole.

3.2 Inspection of Tendons Based on Hierarchy

Based on the factors presented in the previous section, post-tensioning tendons may be prioritized for inspection in accordance with the following hierarchy. Extreme care should be taken to remember that all tendons are important to a bridge. This hierarchy of tendons is for programming inspection resources only and is presented in relation to post-tensioned bridges in Florida only.

3.2.1 Internal Tendons with Suspended Spans

Internal draped tendons in I-girders cantilevering over piers that anchor in dapped hinges and support suspended spans as originally designed for the Sebastian Inlet Bridge and Dupont Bridge present a risk from corrosion. Longitudinally these are statically determinate structures with no redundancy. Loss of support to any dapped hinge on any girder could be serious even though there are multiple girder lines. In addition, the embedded anchors at expansion joints are not readily accessible, nor visible.

3.2.2 Internal Tendons at Dapped Quarter-Point Hinges

In Florida, the only dapped hinges of this type are on three long, continuous span, balanced cantilever segmental ramp structures of the I-595 / I-75 interchange. They exhibited cracking in the hinges soon after construction and were strengthened by external tendons. Original and repair tendon anchors are embedded and not easy to inspect. Loss of the original or repair tendons from corrosion would locally weaken the structure and induce redistribution of internal forces and stresses. The propped cantilever could actually fail with the failure of either corbel at the dapped hinge.

3.2.3 Bottom Internal Continuity Tendons at Expansion Joints

There may be as few as two such tendons passing through the bottom slab in the end sections of the end spans near expansion joints. There is risk of exposure and possible recharge of any incompletely grouted ducts at end anchors near any leaky expansion joints. If there were only two tendons, loss of one would significantly weaken this zone. However, being anchored in blisters and diaphragms, the tendons are accessible for inspection.

3.2.4 Span-By-Span External Tendons – Expansion Joint Spans

External tendons in the end spans of span-by-span structures at expansion joints are exposed to possible recharge of the tendon ducts or anchors by water and deleterious material if the grouting is incomplete. Usually, there are relatively few tendons (6 to 8) in each such span. Loss of a tendon would reveal itself similar to those that have already occurred at Niles Channel and Mid-Bay. Lack of continuous bonding can result in sudden tendon failure when the tendon pulls out of the end diaphragm.

3.2.5 Continuous Drop-In Spliced Girder Tendons

Integrity of the structure can be susceptible to shrinkage of cast-in-place concrete at splices which, in turn, can lead to pathways for ingress of contaminants to the ducts and concrete surrounding the duct splices – both must be good for corrosion protection. Corrosion and loss of any internal tendons would lead to an internal redistribution of forces inducing higher shear at piers and higher flexure in the spans. The structure would then tend toward behavior similar to that of a suspended span bridge.

3.2.6 Span-By-Span External Tendons – Interior Spans

External tendons in the interior spans of span-by-span structures – unlike an exposed end span where recharge of incomplete grouting might occur – are unlikely to suffer recharge. However, they may have not been fully grouted during construction or the tendon ducts could have been damaged or breached. These need to be examined because there are relatively few (typically 8 to 6) within a span. Loss of a tendon would reveal itself similar to that in Span 28 of the Mid-Bay Bridge where the failure was initiated by local corrosion at a puncture of the duct. With only 6 tendons, the loss of one tendon represented an approximate 17% of the total prestressing effects.

3.2.7 Precast Cantilever Tendons Anchored on Segment Face

Internal cantilever tendons of segmental box section superstructures that anchor on the joint faces of the precast segments are not readily accessible and require invasive inspection and maintenance procedures.

3.2.8 Precast Cantilever Tendons Anchored in Blisters

Cantilever tendons of segmental box section superstructures that anchor in blisters on the inside of the box superstructure can be inspected at the anchors for adequate grouting or evidence of possible corrosion. These bridges still rely on the epoxy at precast joint for corrosion protection.

3.2.9 Cast-In-Place Cantilever Tendons Anchored on Segment Face

Cantilever tendons of cast-in-place bridges where tendons anchor on faces of construction joints are not readily accessible for inspection. However, ducts can be made continuous and can be offset from the construction joint. Also, there is typically a continuity of mild reinforcing across the joints.

3.2.10 Mid-Span Bottom Internal Continuity Tendons

These tendons are typically internal to the bottom slab of interior spans of bridges built in balanced cantilever. There are usually 4 or more tendons of this type providing continuity across the midspan closure joints. Leaking epoxy joints between precast segments may allow water to enter the interior of the box. If this is not drained but collects against anchor blisters and diaphragms, it may then seep into tendons that were not fully grouted or tendon anchors. Corrosion damage of a tendon is then possible.

3.2.11 Continuous AASHTO Girder/Bulb-T Tendons

Internal tendons continuous through splices of I-girders over interior piers might be susceptible to infiltration through shrinkage separation cracks and flexural cracks in the slab or any local concrete honeycombing of the cast-in-place concrete at the duct splices. These effects can be overcome by staged application of the post-tensioning to both the non-composite and composite cross sections. Loss of tendons would lead to redistribution of internal stresses - increasing those in mid-span regions.

3.2.12. Mid-Span Top Internal Continuity Tendons

Internal continuity tendons in the top slab at mid-spans of segmental boxes are usually structurally redundant or are provided for rare load combinations that diminish with creep redistribution. Their loss would induce a redistribution of internal stresses and loads would be transferred to the cantilevers and other spans. However, they are seldom considered critical after creep redistribution has occurred. Anchors for these tendons are in blisters inside the box where they are visible and can be inspected for adequate grout or evidence of corrosion. Though they are not easily replaced, there are typically blisters present that were used for anchoring temporary post-tensioning bars during construction. These blister could be used to replace reduced capacities.

Chapter 4 – Improved Durability of Post-Tensioned Bridges

The Florida Department of Transportation is committed to continued development of post-tensioned bridges as a viable solution for many of Florida's infrastructure needs. The challenge, in light of recent instances of corrosion of some post-tensioning tendons, is to consistently produce prestressed bridges with highly durable post-tensioning. The Department defines a durable structure as one that serves its design purpose over the intended life of the bridge, while requiring only routine inspection and maintenance.

Consistent production of durable structures and durable post-tensioning is affected by many factors that become critical at different stages in the life of the structure. The selection of materials and post-tensioning details by the Designer has the first and foremost impact on the resulting durability. During construction the Contractor's ability to effectively build in accordance with the plans and specifications is critical to creating durable structures. Finally, over the service life of the bridge, inspectors and maintainers must be familiar with symptoms and remedies available to ensure the long-term durability of structures with post-tensioning tendons.

Past performance of post-tensioned bridges in Florida has shown that improper consideration for important design, construction and maintenance features leads to reduced durability. Furthermore, even where post-tensioning tendons have been installed and maintained with existing appropriate standards of care on the part of designers, contractors, and maintainers, there have still been instances where high durability has not been achieved. Consequently, additional requirements are needed to produce a design, construction and maintenance environment that consistently produces durable post-tensioned bridges.

In response to this need, the Department is taking a new direction to produce more durable post-tensioned bridges, based on a five-part strategy. The components of this strategy, and the requirements that further define them, are devised to raise the level of performance in design, construction, and maintenance so that confidence in post-tensioned structures is consistently achieved. The Department's new direction, as expressed by the five strategy components, is shown in Figure 4.1.

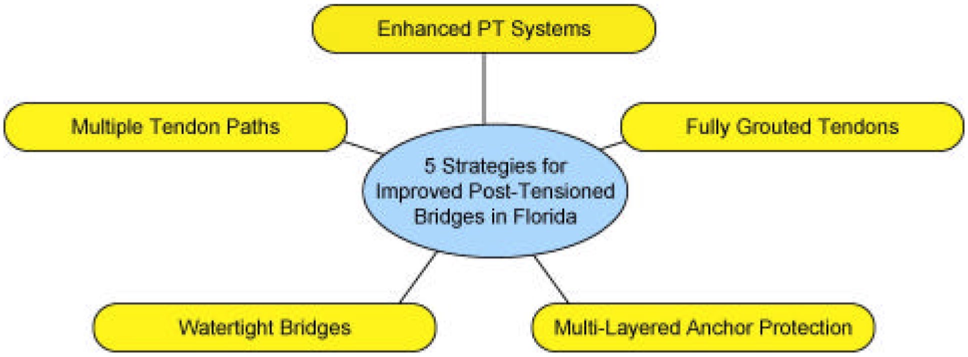


Figure 4.1 – Five-part strategy for more durable post-tensioned bridges in Florida.

The history of post-tensioned bridges and the types of post-tensioning tendons in Florida have been presented in Chapters 1 through 3 of this Volume. The remainder of this Chapter further defines the five strategy components by giving specific requirements to achieve more durable post-tensioned bridges.

Recognizing the need to make immediate improvements, the Department has focused its strategy to elevate the performance of currently available post-tensioning systems in order to provide an appropriate, high level of confidence in Florida's post-tensioned bridges. The Department recognizes the changing state-of-the-art of post-tensioning systems and encourages innovation. The five-part strategy has been developed to accept the continued development of post-tensioned bridges. Strategy requirements may change as new, improved systems become available, but the strategy itself remains intact.

4.1 Strategy 1 – Enhanced Post-Tensioning Systems

Historical Overview

Originally, for 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, in many instances, grouted tendons were later found to contain air voids. Although the grout did not prevent ingress of contaminants, it was found to surround or coat the post-tensioning steel in a chemically passive environment. Galvanized spiral wound ducts also played a secondary role in corrosion protection by allowing excess water in the grout to pass through the seams of the duct and be absorbed by the surrounding concrete and through sacrificial corrosive action. 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 compensated by the application of epoxy when joining precast segments at match-cast joints. Hence, at joints, the epoxy and grout provided corrosion protection.

The introduction of external post-tensioning tendons also altered the nature of the corrosion protection system. As the principal means of corrosion protection, concrete cover exists only where tendons pass through deviators and diaphragms. At locations in between, the external tendon passes through smooth, high-density, polyethylene pipe. Grout was intended to fill the ducts to prevent the intrusion of contaminants. It would also surround the steel tendon in a chemically passive environment. Polyethylene pipe filled with grout became the means of protecting the tendon against corrosion.

While these different tendon types evolved in conjunction with bridge construction methods, there was no significant furthering of original concepts for post-tensioning corrosion protection. Recent investigations in Florida have exposed several fallacies with regard to the assumed roles of the various components of the corrosion protection system. Some of these are:

- Concrete cover has been breached by shrinkage cracks at construction joints and concrete pour backs of blockouts in the post-tensioned superstructure.

- Corrosion protection of internal tendons has been negated by imperfect sealing of epoxy joints in precast segmental bridges. The imperfect sealing was the result of improper application of epoxy, overly aggressive cleaning of the match-cast faces by sand or high-pressure water blasting, and imperfect duct seals at the bulkhead and match-cast segment during casting.

- Grouting procedures have produced voids in tendons due to insufficient filling of ducts and the use of grout material that allowed bleed water and the accumulation of entrapped air.

- Although galvanized ducts offered some galvanic protection, discontinuous ducts at precast segment joints along with imperfect epoxy joint seals allowed direct access for water to tendons that were not always fully grouted.

- High-density polyethylene ducts of some external tendons suffered splits, allowing moisture direct access to grout or strands.

- 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.

Levels of Protection

To establish a new direction for enhanced post-tensioning systems it is important to first define the various levels of protection available to guard against tendon corrosion. Figure 4.2 shows six levels of protection available for typical post-tensioning tendons. Next, the effect that a particular method of construction has on the integrity a level should be established. With these considerations appropriately made, various levels of protection can be combined to satisfactorily protect a tendon from unwanted corrosion.

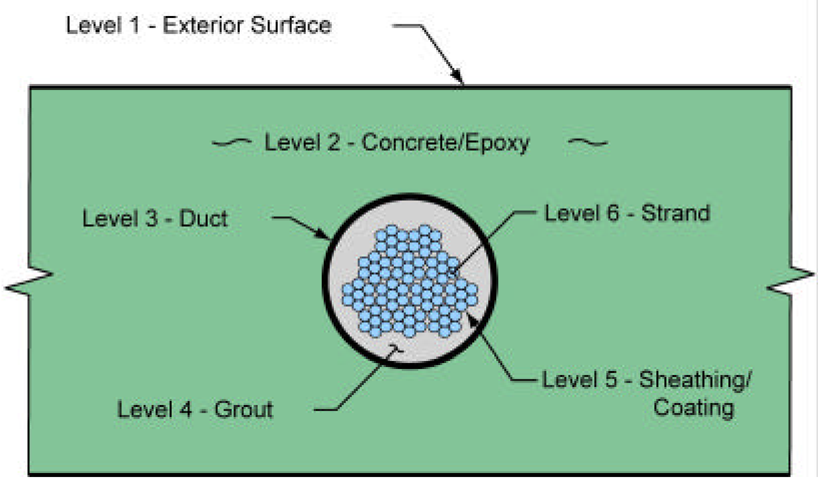


Figure 4.2 – Levels of Protection for Corrosion Protection

The six levels of protection shown in Figure 4.2 are discussed in the following bulleted paragraphs.

- Level 1 – Exterior Surface: The interface between the post-tensioned concrete structure and surrounding atmosphere can play a role in corrosion protection. Appropriate sealing of such surfaces will help keep unwanted contaminants from attacking post-tensioning tendons. Certain overlays, membranes, and wearing surfaces may provide some protection at a roadway surface. However, in Florida, these are primarily for rideability and are subject to wear under traffic. The Department discounts the roadway surface from participating as an exterior surface barrier for corrosion protection. Therefore, effective and proper sealing of other structural surfaces can constitute a level of protection.

- Level 2 – Concrete / 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 the use of either full-length ducts or properly mechanically coupled or sealed ducts. For external tendons, durable plastic pipe ducts can be used, with sealed connections, between steel pipes embedded in deviators and pier segments. Ducts for internal tendons are typically discontinuous at match-cast joints in precast segmental bridges. Duct couplers, such as “Liaseal” by Freyssinet, have been developed, and are being implemented in Florida on select projects. Similar competitive innovations are encouraged. A continuous and sealed duct provides an effective level of protection.

- Level 4 – Grout: Good quality is a key ingredient of current tendon protection systems. The Department has recently completed modifications to FDOT Standard Specification 938 “Post-Tensioning Grout”. New features of this revised specification include pre-bagged, pre-approved grout, improved installation procedures, and requirements for certified grouting personnel.

- Level 5 – Sheathing: An opportunity exists to provide corrosion protection between the grout and the strands. Both greased and sheathed mono-strands and epoxy coated (flo-fill) strands are available. There is not a great deal of experience in the placement of these types of sheathed or coated strands either individually or in bundles for large tendons in bridge construction and there is concern that the sheathing or coating may not necessarily remain intact during installation. Current estimates indicate that material cost for epoxy-coated strand is 3.5 times that of bare strand.

- Level 6 – Strand or Bar: The sixth opportunity for protecting the tendon lies in the main tension element itself. Stainless steel is available for strands or bars, though at considerable expense. Also, the mechanical properties of stainless strand are slightly inferior to normal strand. Even so, considering the nature of the application, the effort and expense may be warranted. Stainless clad strands are being produced in Great Britain but have not been widely used in the United States. The material cost for solid stainless strand is approximately 10 times, and stainless clad strand 5 times, the cost of bare strand. Carbon fiber strands provide another option for corrosion protection at the level of the main tension element. Tendons using these strands have been developed in recent years but have not been used in Florida bridge projects.

Strategy Component

The first strategy implemented for producing more durable post-tensioned bridges is to enhance current post-tensioning systems and include multiple levels of protections.

Strategy 1 - Enhanced Post-Tensioning Systems

All post-tensioning tendons shall be fabricated using enhanced post-tensioning systems.

Specific requirements of this strategy are:

Requirement 1.A: *All post-tensioning tendon systems for use in Florida bridges shall be pre-approved by the Department and selected from the Qualified Product List.*

Requirement 1.B: *All post-tensioning tendons in Florida shall be protected by a continuous three-level system of corrosion protection.*

The Department recognizes that corrosion protection systems for post-tensioning tendons continue to be developed and enhanced. However, considering current construction practice, three-level corrosion protection systems in Florida will incorporate ducts completely filled with an approved grout. This constitutes one level. Two other levels of protection are to be provided by a combination of the levels shown in Figure 4.2

Requirement 1.C: *Except in areas of sharp curvature, post-tensioning tendons shall be placed within plastic ducts. Plastic ducts shall be pre-approved by the Department and selected from the Qualified Products List.*

Internal post-tensioning tendon ducts shall be plastic and mechanically attached to the anchorage assemblies. For internal tendons, plastic duct shall be corrugated with either a continuous spiral or hoop layout. External post-tensioning tendon ducts shall comprise a combination of smooth plastic pipe positively connected to steel pipes embedded at diaphragms and deviators. Only steel pipe shall be used for sharply curved ducts. Smooth plastic pipe shall have a D/R ratio no greater than 15.5. Steel pipe shall be schedule 40.

Requirement 1.D: *All duct connections shall be positively sealed. Connections shall be included in the acceptance requirements for plastic ducts for the Qualified Products List.*

For internal tendons, positively sealed connections shall be made between embedded lengths of corrugated plastic duct. For external tendons, positively sealed connections shall be made between embedded steel pipe duct and smooth plastic pipe duct and between lengths of smooth plastic pipe duct.

Requirement 1.E: *All grout for post-tensioning tendons in Florida shall be prebagged and pre-approved grout in accordance with FDOT Standard Specification 938.*

Requirement 1.F: *All post-tensioning tendons shall be capped with permanent, heavy-duty plastic caps incorporating an o-ring seal at the interface between cap and anchor plate.*

Requirement 1.G: *All post-tensioning tendon ducts shall be pressure tested in accordance with the Standard Specifications prior to grouting.*

4.2 Strategy 2 – Fully Grouted Tendons

The second strategy to improve the durability of post-tensioning tendons deals with the complete filling of tendon ducts with appropriate grout material in order to maximize the effectiveness of the grout in its two-part role in corrosion protection, namely: the elimination of voids in which contaminants may migrate and the development of a chemically basic environment.

Strategy 2 - Fully Grouted Tendons

All post-tensioning tendons shall be completely filled with grout during construction.

Specific requirements of this strategy are:

Requirement 2.A: *All anchorages shall be accessible for stressing, grouting, inspection throughout all processes of installation and protection – including permanent grout caps.*

Anchorages may be located on the end faces of precast segments as long as sufficient access is provided to accomplish this requirement. However, blockouts extending through to the top of the top slab shall not be used for this purpose.

Requirement 2.B: *Injection of grout at the low point is required for all post-tensioning tendons.*

For generally horizontal tendons, vents shall be provided at all high points and 3 feet to 6 feet beyond crests in the direction of grouting. Drains shall be provided at all low points.

For vertical tendons, grouting shall proceed in stages in order to eliminate or minimize bleed. New grout shall be injected at the lowest point of the next stage. Injection ports shall be provided as necessary to facilitate grouting in stages.

Requirement 2.C: *With regard to fully grouted tendons, Contract Plans shall be consistent with Semi-Standard Post-Tensioning Drawings.*

The Contract Plans shall include supplemental notes to provide specific information referred to on the Semi-Standard Post-Tensioning Drawings.

Requirement 2.D: *Grouting shall be performed and inspected by personnel certified in accordance with Department requirements.*

Requirement 2.E: *The rate of injection of post-tensioning grout shall not be less than 8 gallons per minute or more than 12 gallons per minute.*

Requirement 2.F: *Grouting shall continue until the grout ejected at each vent and from the end of the tendon is of the same quality as that being injected.*

All vents shall be checked again and more grout injected if necessary. The tendon shall then be locked off and the pressure increased to no more than 75 psi. After holding the pressure at 75 psi for 2 minutes, grout vents shall be “burped” in a logical sequence to eject any entrapped air. With all vents again closed pressure shall again be held at 75 psi for 2 minutes and then reduced to 30 psi and the grout allowed to attain its’ initial set.

Requirement 2.G: *After the grout has set but before applying any protection to the anchors, (in accordance with FDOT specifications), all tendon high points and anchorages shall be probed and inspected for the presence of voids. Any voids shall be filled with grout using an approved technique (secondary vacuum assisted grouting).*

4.3 Strategy 3 – Anchor Protection

Significant corrosion of post-tensioning tendons in Florida has been the result of lack of adequate protection at anchorages. In addition to the localized protection of the anchorage components, anchor protection prevents ingress of contaminants in to the tendon itself.

Strategy 3 - Anchor Protection

All post-tensioning tendon anchors shall have a minimum of four levels of corrosion protection.

Specific requirements of this strategy are:

Requirement 3.A: *The anchorage protection system on the Contract Plans shall comply with the Department’s Semi-Standard Post-Tensioning Drawings.*

The Contract Plans shall include supplemental notes to provide specific information referred to on the Semi-Standard Post-Tensioning Drawings.

Requirement 3.B: *Anchorages shall be protected by a four-level protection system comprised of grout, heavy-duty permanent grout caps with sealing o-rings, an applied coating, and enclosure in a concrete structure or pourback.*

It is important to make a distinction between anchorages that are directly exposed to water and waterborne contaminants and those that are not. Those that are directly exposed will require the application of the fourth level of protection. Those tendons that are not directly exposed may count on enclosure within a box girder superstructure as the fourth level of protection, provided the girder is watertight and well drained.

Examples of anchors directly exposed to water and water borne contaminants include:

- Anchors at expansion joints of balanced cantilever and span-by-span structures
- End anchors at expansion joints of post-tensioned I- Girders and bulb-T's
- Anchors buried under a deck-slab pour-back to an I-Girder or bulb-T
- Anchors at expansion joints of structures cast-in-place on falsework
- Anchors in a cap at the top of vertical tendons
- Anchors at the ends of hammerhead pier caps and straddle beams

Examples of anchors not directly exposed to water and water borne contaminants include:

- Anchors in blisters, deviators or ribs at top or bottom inside a hollow section
- Face anchors in inspection recesses open to the interior of a hollow section
- Anchors in diaphragms at interior piers of a hollow section (but not at end diaphragm)

Requirement 3.C: *Post-tensioning tendons will be sealed at all times to prevent the entrance of water and water borne contaminants.*

After casting a part of a post-tensioned bridge, whether on-site or in a precast yard, and prior to installation of the post-tensioning tendons, ducts shall be sealed to prevent the entrance of contaminants. After stressing the tendons, grout caps shall be installed immediately. Vents and ports in the anchorages and grout caps shall be sealed with a threaded plug from the time the tendons are stressed and until they are grouted. The threaded seals shall be removed for grouting and then replaced prior to providing anchorage protection.

4.4 Strategy 4 – Watertight Bridges

Joints, blockouts, holes and other openings in the top slabs of bridges are required for certain types of bridge construction. Experience with post-tensioned bridges in Florida, however, indicates that water carrying corrosive contaminants often migrates through improperly cast secondary pours and patches and can come in direct contact with post-tensioning tendons. As a result the following strategy is implemented:

Strategy 4 - Watertight Bridges

All bridge decks of post-tensioned bridges shall be watertight.

Specific requirements of this Strategy Component shall be:

Requirement 4.A: *All joints between precast segments in segmental construction shall be sealed with epoxy.*

Epoxy shall be applied over the entire face of both segments being joined.

Requirement 4.B: *In addition to controlling tensile stresses in accordance with applicable design codes, there shall be no permanent tensile stress induced by post-tensioning and sequential construction under self-weight and superimposed dead load.*

Requirement 4.C: *The number of blockouts and wholes in decks shall be minimized. All blockouts and holes shall be tapered in order to facilitate filling and secure containment of the concrete pour-back.*

All blockouts and holes in bridge decks shall be filled with an approved, air cured, concrete of high strength, high bond, and low shrinkage. After the pourback has cured the pourback shall be sealed with an approved crack healer/sealer.

Requirement 4.D: *Exposed external structural surfaces of secondary pours shall be effectively and properly sealed using approved sealing materials.*

Sealing materials include methyl methacrylate and other similar coatings. Class V finish does not constitute a sealing material.

Requirement 4.E: *Roadway surfacing and membranes are not considered a protection barrier for post-tensioning.*

Requirement 4.F: *On the Contract Plans details shall be shown for drip notches or flanges in locations where water may directly flow to any component of the post-tensioning system.*

Requirement 4.G: *In box girder bridges, bottom slab drains shall be placed to prevent water that enters the box girder from ponding in the vicinity of post-tensioning components, with proper account for the effects of bridge grade and cross slope.*

4.5 Strategy 5 – Multiple Tendon Paths

The use of a few large tendons to prestress a bridge greatly increases the impact of corrosion damage to a single tendon. Providing more tendons of smaller size reduces the impact of individual tendon corrosion on bridge performance.

The impact on post-elastic and ultimate behavior of bridges that have lost prestress as a result of corrosion varies with type of post-tensioned bridge. Bridges with bonded continuous mild reinforcing steel, designed to carry the structure when prestressing steel is corroded, can provide needed ductility to give indications of distress. Bridges with external, unbonded prestressing systems can be inspected and tendons replaced if necessary. Post-elastic deformations of these bridges provide significant signs of possible distress in the post-tensioning tendons. Those bridges with internal tendons that cannot be inspected or replaced, and that do not have continuous mild reinforcing are much less ductile than the previously mentioned bridges. Consequently, an appropriate response to guarding against the effects of loss of prestressing as a result of corrosion is to provide post-tensioning in these bridges above that level required to resist the design loads. External, unbonded tendons are preferred for supplying this additional prestressing.

Strategy 5 - Multiple Tendon Paths

Post-tensioned bridges shall be designed to provide multiple tendon paths using a greater number of smaller sized tendons.

Specific requirements of this strategy are:

Requirement 5.A: *Post-tensioning layouts shall be designed to maximize the number of post-tensioning tendon paths through the use of more tendons of smaller (force) capacity*

Requirement 5.B: *The loss of the most critical tendon at any location shall not result in an Inventory or Operating Rating less than 1.0 in accordance with FDOT load rating criteria*

Requirement 5.C: *During the design, consideration shall be given, within the post-tensioning layout and details, to compensate for loss of prestress due to corrosion. In doing so, consideration shall be given for differences in bridge type, construction method and reliability of the proposed post-tensioning system as related to long-term durability.*

Appendix A - Definitions

Definitions used in this and subsequent Volumes pertaining to increased durability of post-tensioned bridges are in accordance with the AASHTO *Standard Specifications for Highway Bridges*, the AASHTO *Guide Specifications for Design and Construction of Segmental Concrete Bridges*, and the Post –Tensioning Institute *Specification for Grouting of Post-Tensioned Structures*. Additional definitions not in these referenced documents are given in the following sections.

A.1 Post-Tensioning Systems

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

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

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

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

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

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

Post-Tensioning System: A proprietary system where the necessary hardware (anchorages, wedges, strands, bars, couplers, etc.) is supplied by a particular manufacturer or manufacturers of post-tensioning components.

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

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

Wedge: Small conically shaped steel components placed around a strand to grip and secure it by wedge action in a tapered hole through a wedge plate. (FDOT requires 3-part wedges).

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

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

A.2 Grout Related Definitions

Contamination: Any foreign material found in a tendon at any point in time, the effects of which, if not negated could lead to a lessening of effectiveness of the tendon.

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 through a combination of grouting rate and the workability of the material, where the grout does not completely fill the duct, trapping air as it moves to the low point.

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.

A.3 Continuous and Spliced I-Girders

Camber: The amount by which a precast beam deflects under the action of its own self-weight and the pretensioning applied at the plant and post-tensioning applied on site. (This is technically different to “camber” in the context of segmental construction).

Dapped hinge: A point where the end of one beam or box girder is supported by another by a simple bearing resting upon a seat or step formed by extending the bottom half of the support beam under the top half of the supported beam.

Splice: A cast-in-place connection between the end of one precast I-girder and another. A splice may be short and unreinforced or long and contain reinforcing. Usually, longitudinal post-tensioning is made to pass through a splice between I-girders. A splice of this type makes the beams structurally continuous – as opposed to being able to rotate separately as at dapped hinges.

A.4 Segmental Bridges

Balanced Cantilever (Erection): A method whereby the segments are sequentially erected, in cantilever, alternately on either side of the pier to a point where a closure is cast in place with an adjacent span or cantilever.

Camber: The amount by which the concrete profile at the time of casting must differ from the theoretical geometric profile grade in order to compensate for all structural dead load, post-tensioning, all long-term, time dependent deformations (creep and shrinkage) including all the intermediate erection stages and effects. (The opposite of deflections.)

Casting Cell: Refers to a special formwork arrangement usually consisting of a fixed vertical bulkhead of the cross-section shape at one end and adjustable soffit, side and cores form all designed and assembled into a machine for making a single superstructure segment. A casting cell for a substructure pier shaft segment would consist of exterior and interior side forms and a soffit form that has the cross-section shape.

Casting Curve or Casting Curve Geometry: the curve of casting geometry that has to be followed in the casting cell or bed in order to achieve the theoretical bridge profile and alignment after all the final structural and time dependent (creep and shrinkage) deformations have taken place. The casting curve is a combination of the theoretical bridge geometrical profile grade, alignment and the camber.

Closure Joint: A cast-in-place concrete joint between precast segments used to complete a span.

Deviation Segment: A precast segment within a span that contains a block, rib, or diaphragm for the purpose of deviating (deflecting or changing the path of) an external post-tensioning tendon.

Dry Joint: Where epoxy is not applied between the match cast surfaces of adjacent precast segments during erection. (Dry joints are not allowed in Florida).

Epoxied Joints: Where epoxy is applied to the match cast surfaces of adjacent precast segments before assembling into the final structure.

Erection Elevation: the elevation to which a segment is to be set in the structure at the time it is erected. (This is not necessarily the profile grade but rather the profile grade corrected by the amount of deflection calculated to occur from that stage onwards, at that location.)

Expansion Joint (EJ) Segment: An end segment of the superstructure that rests upon a bearing at an abutment or intermediate expansion pier and that carries a block-out to receive the expansion joint device (finger joint, modular joint, etc.)

Form Traveler: Specialized erection equipment used to erect cast-in-place balanced cantilever bridges comprised of wing, soffit and core forms and supporting trusses. The specialized equipment rests on previously completed portions of bridge superstructure while concrete of the next cast-in-place segment is poured.

Long Line Casting: A method of casting segments on a casting bed of sufficient length to permit the cumulative casting of segments for the entire length of a span or cantilever between field closure pours without repositioning the segments on the casting bed. With this method, the first segment is cast between bulkheads and successive segments are cast between a movable bulkhead on one end and the previously cast segment on the other.

Match Cast: Refers to a precast concrete fabrication process whereby a segment is cast against the preceding segment producing a matching interface that will permit the reestablishment of the cast geometry at the time of erection. Match casting may be accomplished by either the short line or long line casting method.

Modified Cantilever (Erection): A method whereby segments are erected in cantilever from the end of a span previously erected using the span-by-span method.

Pier Segment: That segment of the superstructure resting atop a substructure pier, column or support.

Pier Table: In precast cantilever construction, usually the pier segment and first one or two segments on each side of the pier that are used to provide a beginning platform and accommodate the temporary stability system for the erection of the remainder of the balanced cantilever. In cast-in-place cantilever construction, it is that portion of the structure over the pier, usually 24 to 40 feet long, completed first using formwork; it is then the platform from which form travelers advance to complete other typical cantilever segments.

Progressive Cantilever (Erection) A method whereby segments are erected progressively in cantilever, in one direction, using intermediate temporary or permanent piers or other means, as required, to support the advancing cantilever.

Segment: Refers to a modular section of the superstructure and/or substructure consisting of a certain cross-section shape and length as detailed on the plans.

Short Line Casting: A method of casting segments one at a time in a casting cell between a bulkhead at one end and a previously cast segment at the other. The first segment is cast between the bulkhead and another temporary bulkhead.

Span-by-Span (Erection): A method whereby the segments for one complete span are sequentially erected by aligning them on a support frame, such as a truss, until one or more closures are cast in place. Closures are usually made between the end segments in the span and the adjacent pier or expansion joint segments.

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