Florida Department of Transportation

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SECRETARY

February 7, 2001

M E M O R A N D U M

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District Construction Engineers
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COPIES: Secretary Tom Barry, Assistant Secretary Ken Morefield, District Secretaries David Twiddy, Aage Schroeder, Edward Prescott, Rick Chesser, Mike Snyder, Jose Abreu, Ken Hartmann, and Jim Ely, State Highway Engineer Freddie Simmons, Director, Office of Design Billy Hattaway; Doug Edwards (FHWA), Structures Design Engineers William Domico, Bob Nichols, Jack Evans and Dick Kane, Public Information Administrator

SUBJECT: Temporary Design Bulletin DB-C01-1 and Commentary

All projects in design and to be let after May 2001 will include the following provisions which replace **Article 7.15.11 of the *Structures Design Guidelines*** (LRFD) and **Article 8.11 of the *Structures Design Guidelines*** (LFD):

> Permanent and temporary post-tensioning termini that are required to be located in either the top or bottom slab of box girder bridges shall be anchored by means of interior "blisters." All anchor blisters for tendons shall terminate no closer than 18" from the segment face. Contractor redesigns using tendons anchored on the face of segments will be allowed, with approval of the State Structures Design Engineer, provided that the tendon is grouted and the anchorage inspected before the next segment is assembled. Blockouts that extend to exterior surfaces of the slabs are not permitted.

Special Instructions

Projects let after May 2001 and before December 2001 which are currently detailed with anchorages on the segment face shall be redesigned to be in accordance with these requirements or Plan Notes and Specifications Revisions need to be added to the plans requiring the contractor to comply with these provisions.

Commentary:

Designers and contractors may not have realized that the new construction specification will require each non-blistered tendon to be grouted after each pair of segments are erected; thus slowing down construction. In addition to providing for a reasonable construction rate we also gain the following benefit: If a joint between segments were to leak, as has been the case to date, water will not pass over the anchorage. This leakage does not appear to be as serious a concern for cast-in-place concrete structures as for precast segmental construction.

Background

This bulletin is being issued to augment DB-C00-5 in an effort to provide a brief background to new changes incorporated in Florida Department of Transportation Specifications, Section 453, Epoxy Jointing of Precast Segments; Section 460, Post-Tensioning; and Section 938, Post-Tensioning Grout. All restrictions in DB-C00-5 are still to be adhered to. The draft report " Mid-Bay Bridge Post-Tensioning Evaluation" which is an attachment to this bulletin provides engineers and contractors with information on the conditions of the grout found at one post-tensioned Florida Bridge. Subsequent to this inspection, other post-tensioned structures in the State have been inspected to determine the extent of grout voids in these bridges. Preliminary results indicate that several of these post-tensioned bridges will also require grout injection of the anchorages as required in the Mid-Bay Bridge. The FDOT has retained the services of Corven Engineering to synthesize post-tensioning practices here in Florida.

The draft report entitled "Mid-Bay Bridge Post-Tensioning Evaluation" represents the first phase of the work by Corven Engineering, Inc. (Corven) to evaluate post-tensioned bridges in Florida. In the next phase of work, Corven will review the details and condition of several of Florida's post-tensioned bridges and structurally analyze three of these bridges to further our understanding of how our post tensioned bridges are performing. The last phase of work includes the development/enhancement of "The Design, Construction, Construction Inspection, Maintenance Inspection, and Testing of Post-Tensioned Bridges."

As a result of the extensive post-tensioning inspection efforts being made around the State, it is believed that these efforts will identify new post-tensioning methodologies by the fall of 2001. In the meantime, for all projects in construction, upcoming in lettings, and in design, the following changes are required:

Jobs in Construction

- Nearly all projects have changed over to the new Section 938 Post-Tension Grout material specification.
- Employ low point-up grouting, to the maximum extent possible.
- Inspect all trumpets to verify trumpets are completely grouted.
- Give special attention to venting locations and grouting rates. [Grout procedure training is being offered through the State Construction Office. (Contact Steve Plotkin at (850) 414-4155).]

Upcoming Lettings (Beginning February 2001)

Specifications have been modified to preclude the use of post-tensioned systems that cast the pour-back prior to tendon grout placement. FDOT is now requiring that all anchorages have grout caps removed and that grout injection ports are drilled and inspected (probed) to verify that the anchorages are full of grout. In an effort to increase the probability of a successful grouting operation, a colloidal mixer, low point-up grouting, and new grout material have also been required as previously stated. The Specification, Section 453, Epoxy Jointing of Precast Segments, requires both faces of every segment to be coated with epoxy. This is a requirement for both balanced cantilever and span-by-span and is intended to improve durability by limiting moisture intrusion into the precast box segments as has been observed in several post-tensioned structures around the State.

In order to minimize the risk of contamination or recharge with water of a post-tensioned system, the time the system will be permitted to be unprotected has been established. This established time duration limit between strand placement, stressing, and grouting; tail cutting; pour-back material casting; bituminous coating application; and expansion joint installation will protect future post-tensioning installations.

Future efforts include the use of water tight shrink wrapped joints and, between segments, mechanical duct couplers, such as the Freyssinet “Liaseal” coupler, which is being utilized as an experimental product on the upcoming Royal Park Bridge replacement. If the precast option is constructed, FDOT will gather firsthand knowledge of this promising device.

During the coming year we will develop more information and details addressing reliability, durability and installation limitations of our past systems and additional insight to needed improvements. These positive changes will not be the last made in our effort to obtain 75+ years of service from our post-tensioned bridges. If you have any questions about a specific project, please contact your Area Engineer.

WNN:hs

Attachments

Florida Department of Transportation
District 3

Draft Report

This report summarizes inspections, tests, analyses, and repairs of the Mid-Bay Bridge post-tensioning system

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February 8, 2001

Mid-Bay Bridge

Post-Tensioning Evaluation

Mid-Bay Bridge Post-Tensioning Evaluation

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Preface

The Florida Department of Transportation did not design or oversee the construction of the Mid-Bay Bridge. The Florida Department of Transportation has entered into an operation and maintenance agreement with the Mid-Bay Bridge Authority for the purposes of preserving this piece of infrastructure.

Disclaimer

This Draft Report is published to document the progress to date of the inspection, testing, rehabilitation and analysis of the post-tensioning system of the Mid-Bay Bridge. The concepts, ideas, and thoughts expressed in this report are not solely those of the author. The information presented herein is primarily a consolidation of work performed by others. This Draft Report is a work in progress and is subject to change in all areas. After complete findings are known and all repairs are made to the post-tensioning system, a Final Report will be produced.

Chapter 1 – Introduction

1.1 Overview

The Mid-Bay Bridge, Florida Bridge No. 570091, is a precast segmental bridge crossing Choctawhatchee Bay in Okaloosa County, Florida. The bridge carries FL 293 between US 98 near Sandestin and SR 20 east of Niceville. A location map of the bridge is given in Figure 1.

On August 28, 2000, during a routine inspection of the Mid-Bay Bridge, a post-tensioning tendon in Span 28 was observed to be significantly distressed. The polyethylene sheathing surrounding the tendon was cracked, exposing the tendon's high strength prestressing strands and surrounding cementitious grout. Several of the strands of the post-tensioning tendon were fractured.

Concern raised from this observation led to an immediate "walk-through" inspection to verify if other post-tensioning tendons were exhibiting similar signs of distress. A post-tensioning tendon in Span 57 was found completely failed at the north end of the tendon as evidenced by pull out of the tendon from the expansion joint diaphragm.

As a result of these preliminary findings, a more complete inspection, testing and analysis program was developed to attempt to identify the source and extent of corrosion in the post-tensioning tendons and to develop necessary remedial action. This report presents the findings of these inspections, tests and analyses.

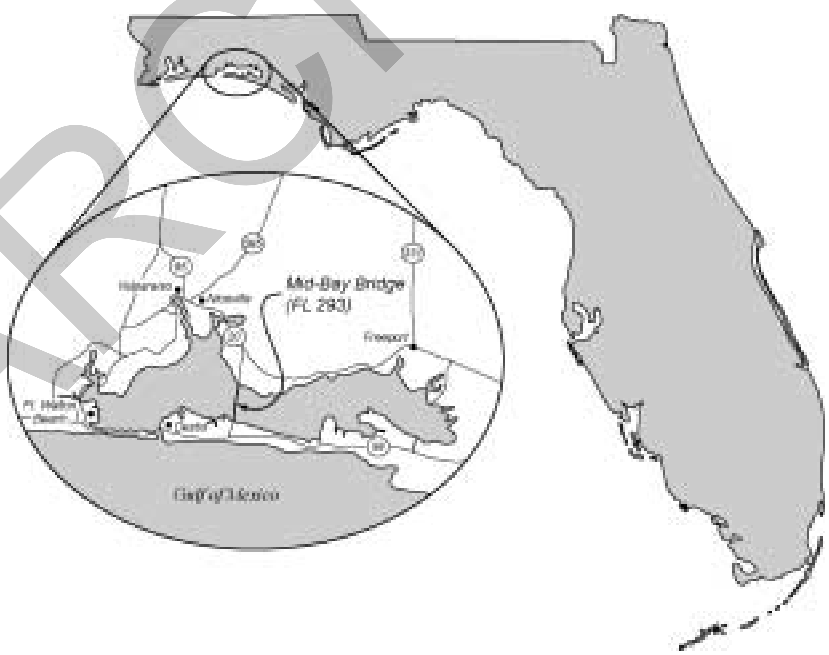


Figure 1.1 – Location of the Mid-Bay Bridge

1.2 Bridge Description

The Mid-Bay Bridge is a 19,265’ precast segmental bridge crossing Choctawhatchee Bay in Okaloosa County, Florida. The bridge is made of 141 spans, arranged into 25 continuous structural units. All spans of the Mid-Bay Bridge have a length of 136’, except for the 225’ main span (Span 83). The alignment of the bridge is predominately south-to-north, with the beginning of the bridge (Span 1) at the southern end. The arrangement of the spans and continuous units is as follows:

Unit 1:	4 Span Unit	Spans 1 through 4
Unit 2:	5 Span Unit	Spans 5 through 9
Units 3 – 14:	12-6 Span Units	Spans 10 through 81
Unit 15:	3 Span Unit	Spans 82, 83, 84 (136, 225, 136’)
Units 16 – 23:	9-6 Span Units	Spans 85 through 132
Unit 24:	5 Span Unit	Spans 133 through 137
Unit 25:	4 Span Unit	Spans 138 through 141

The typical cross section of the precast segmental superstructure is the single cell box girder shown in Figure 1.2. The bridge has an out-to-out width of 42’-9” and has a depth of 8’. The roadway width between the barrier rails is 40’, providing a 12’ vehicular lane and 8’ shoulder in each direction of travel.

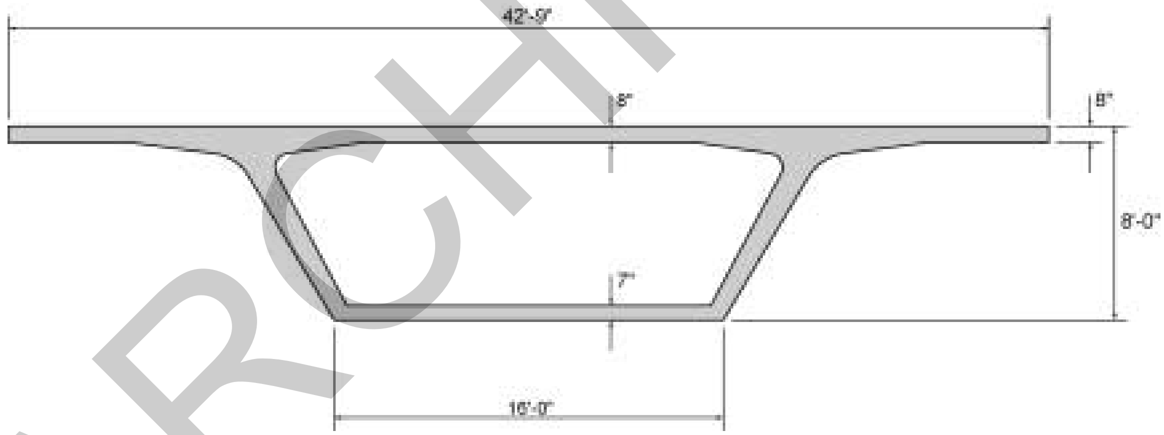
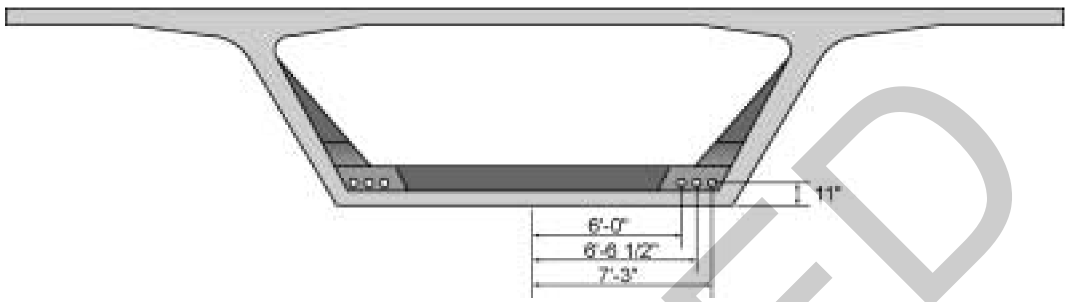
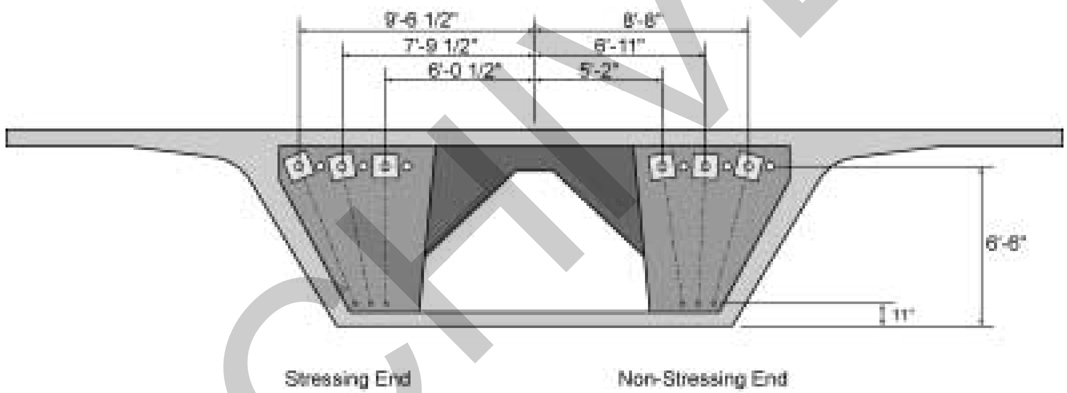


Figure 1.2 – Typical Superstructure Cross Section

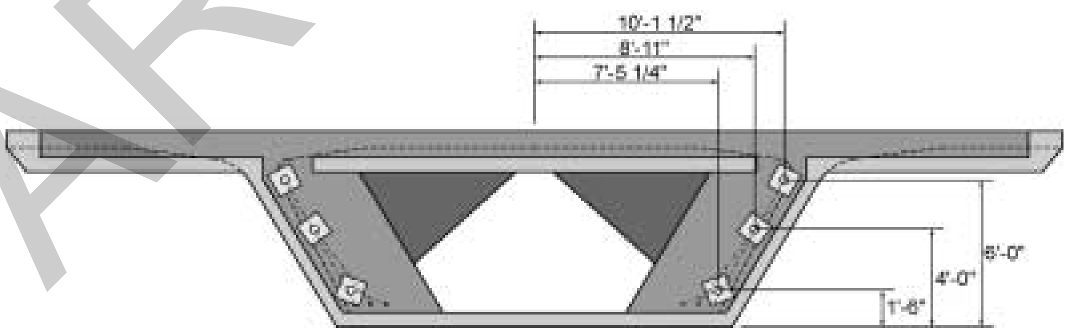
The 136’ spans of the Mid-Bay Bridge are made of four different types of precast segments: Typical Segments, Deviation Segments, Pier Segments and Expansion Joint Pier Segments. Each span has five, 17’-9” long typical segments with a cross section as shown in Figure 1.2. Deviations Segments have the same section as the Typical Segments and are also 17’-9” in length. The Deviation Segments contain concrete diaphragms and bottom slab beams to transfer the force of the longitudinal post-tensioning as it changes profile within the span. Pier Segments are 10’-9” in length, are placed symmetrically over the interior piers, and contain diaphragms to anchor post-tensioning tendons and transfer superstructure forces to the substructure. Two, 5’-3”, Expansion Joint Pier Segments are required at each expansion joint pier between continuous units. The Expansion Joint Pier Segments also anchor post-tensioning tendons and transfer superstructure forces through internal diaphragms. The diaphragm length of the Expansion Joint Pier Segments is 4’11” versus 9’-6” in the Typical Pier Segments. The cross sections of the Deviation Segments, Pier Segments, and Expansion Joint Pier Segments are shown in Figure 1.3. Typical and Expansion Joint Span layouts are shown in Figure 1.4.



Deviation Segment



Pier Segment



Expansion Joint Segment

Figure 1.3 – Segment Types and Post-Tensioning Dimensions

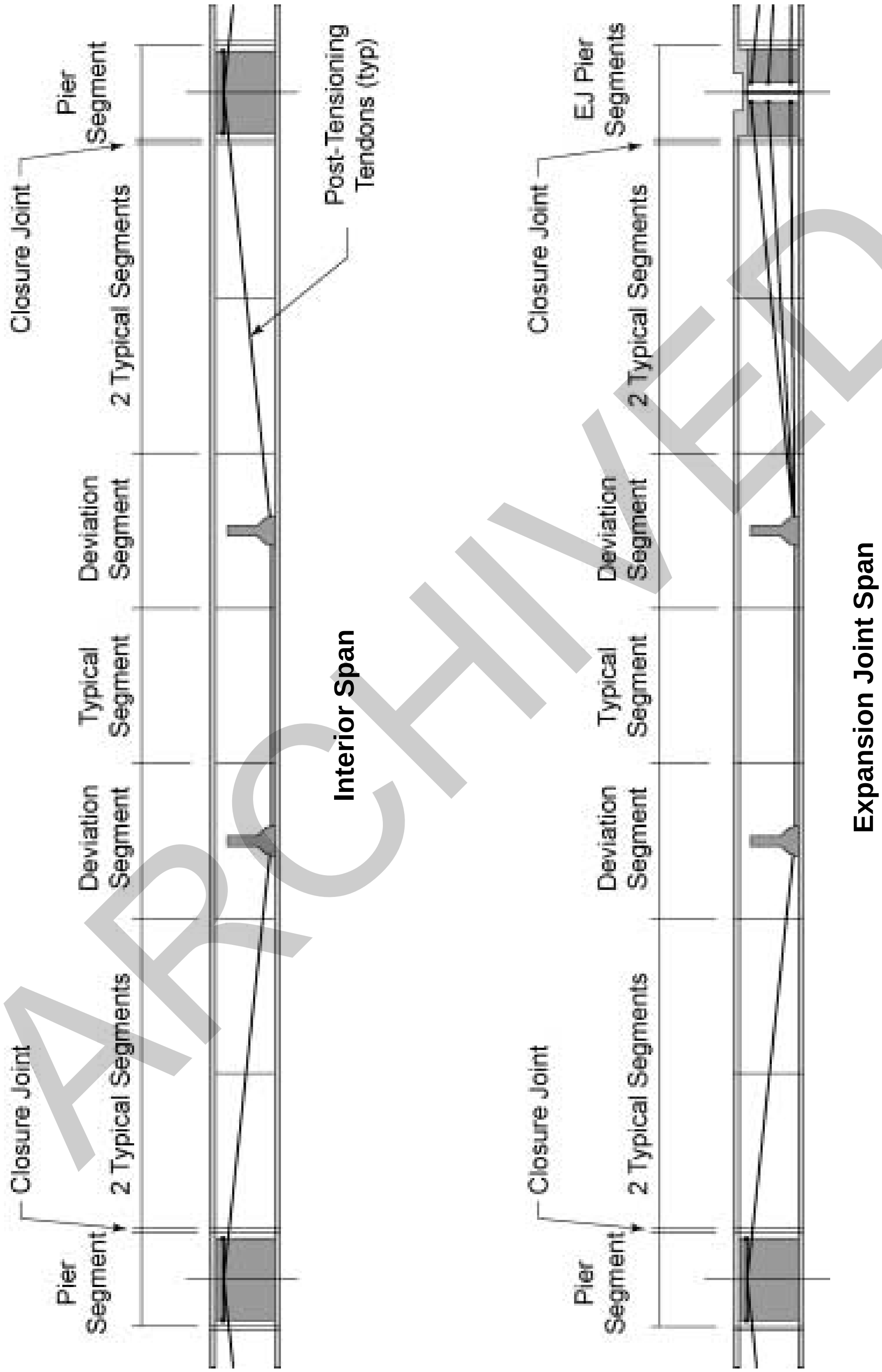


Figure 1.4 – Interior and Expansion Joint Span Layouts

Six post-tensioning tendons support each of the 138 approach spans of the Mid-Bay Bridge. Each tendon is made of 19, 0.6" diameter, 7-wire prestressing strands with a guaranteed ultimate strength of 270 ksi. The post-tensioning tendons are full span in length, anchored in either a pier or expansion joint diaphragm at the ends of the spans. The tendons deviate in plan view at the deviation diaphragms to produce a "draped" profile.

The post-tensioning tendons are encased in steel ducts as they pass through the pier segment diaphragms and the deviation diaphragms. The pier segments are 10'-9" long and provide a 9'-5" long embedment of the post-tensioning tendon in the pier segment diaphragms. The profile of the tendons in the pier segments begins horizontal and then curves downward to give the inclination of the draped tendon geometry. The tendon "high point" in this configuration is distributed over the approximately 4'-6" of tangent duct. The expansion joint diaphragms provide a 3'-10" embedment. The tendon is inclined all of the way through the diaphragm to the anchor. The high point of the expansion joint tendons is at the anchor.

Between the diaphragms of the pier and expansion joint segments, where the tendons are outside of the concrete but inside the box girder, the tendons are protected by polyethylene ducts that are coupled to the steel duct sections. After the post-tensioning tendons are placed and stressed, they are injected with cementitious grout for additional corrosion protection and bond development in concrete diaphragms.

The typical spans of the Mid-Bay Bridge were built using the Span-by-Span method of construction. In this method, an erection truss temporarily supports all segments of a span while post-tensioning is installed and stressed. A typical erection cycle would begin with the advancement of the erection truss from the previously completed span. The pier segment at the beginning of the span was assembled in the previous phase. The pier segment at the end of the span is supported on the erection truss and the next pier. Once the truss is place, the typical and deviation segments are positioned on the trusses and aligned to the appropriate geometry. Next the post-tensioning tendons are installed and blocking placed in the closure joints between typical segments and pier segments. A small amount of post-tensioning is stressed to secure the relative movement of the segments so that the concrete closure joints can be cast between pier segments and the first typical segments. When the closure joint concrete reaches appropriate strength, the remainder of the post-tensioning can be stressed and the tendons grouted, completing the erection cycle.

The direction of erection of the span-by-span construction of the Mid-Bay Bridge was from south to north for Spans 1 to 81, and from north to south for Spans 141 to 85 (descending order). Spans 82, 83, and 84 make up a continuous three span main unit containing the main span. This unit was built using modified balanced cantilever segment construction. The segments of precast segmental bridges can be joined with epoxy to aid in the alignment of the segments and help improve the water-tightness of the box girder. The spans of the Mid-Bay Bridge were built using the span-by-span method of construction and did not use epoxied joints. The three-span main unit was built in modified balanced cantilever using epoxied joints.

1.3 Project Timeline

The inspection, testing and analysis activities presented in this report primarily occurred during the last three months of the year 2000. FDOT inspectors were performing an annual inspection of the bridge on August 28, 2000 when broken wires in Tendon 6 of Span 28 and the failure of Tendon 1 in Span 57 were discovered. The bridge had received its last inspection in early May of the same year, with no significant findings of distress.

Figure 1.5 shows a bar chart schedule of the inspection and repair activities on the Mid-Bay Bridge. Inspection and remedial actions took place immediately following the discovery of the failed post-tensioning. Crews worked multiple shifts around the clock in order to assess the condition of the bridge. Traffic interruptions or limitations were imposed as a result of the findings of the ongoing inspection and testing program. The following list gives the dates of traffic limitations and the impact to traffic:

August 28, 2000 and August 29, 2000	Complete Closure
August 29, 2000 to September 27, 2000	2 Axle Vehicles Only
September 27, 2000 to October 11, 2000	Complete Closure
October 11, 2000 to November 16, 2000	2 Axle Vehicles Only
November 16, 2000 to Present	All Legal Loads, no Permitted Loads

Other traffic impacts were associated with specific tendon removal and replacements:

Span 28 Tendon 6	8 hour nighttime closure
Span 58 Tendon 5	1 hour daytime closure
Span 69 Tendon 3	1 hour daytime closure
Span 63 Tendon 6	1 hour daytime closure
Span 69 Tendon 2	1 hour daytime closure
Span 64 Tendon 1	1 hour daytime closure
Span 58 Tendon 6	1 hour daytime closure
Span 48 Tendon 5	1 hour daytime closure

1.4 Tendon Numbering Convention

A standardized numbering scheme for the post-tensioning tendons of the Mid-Bay Bridge was adopted to help organize the inspection and modification efforts. This numbering scheme is shown for typical piers in Figure 1.6 and for expansion joint piers in Figure 1.7.

Example: Tendon 1 of Span 57 is referred to as Tendon 57-1.

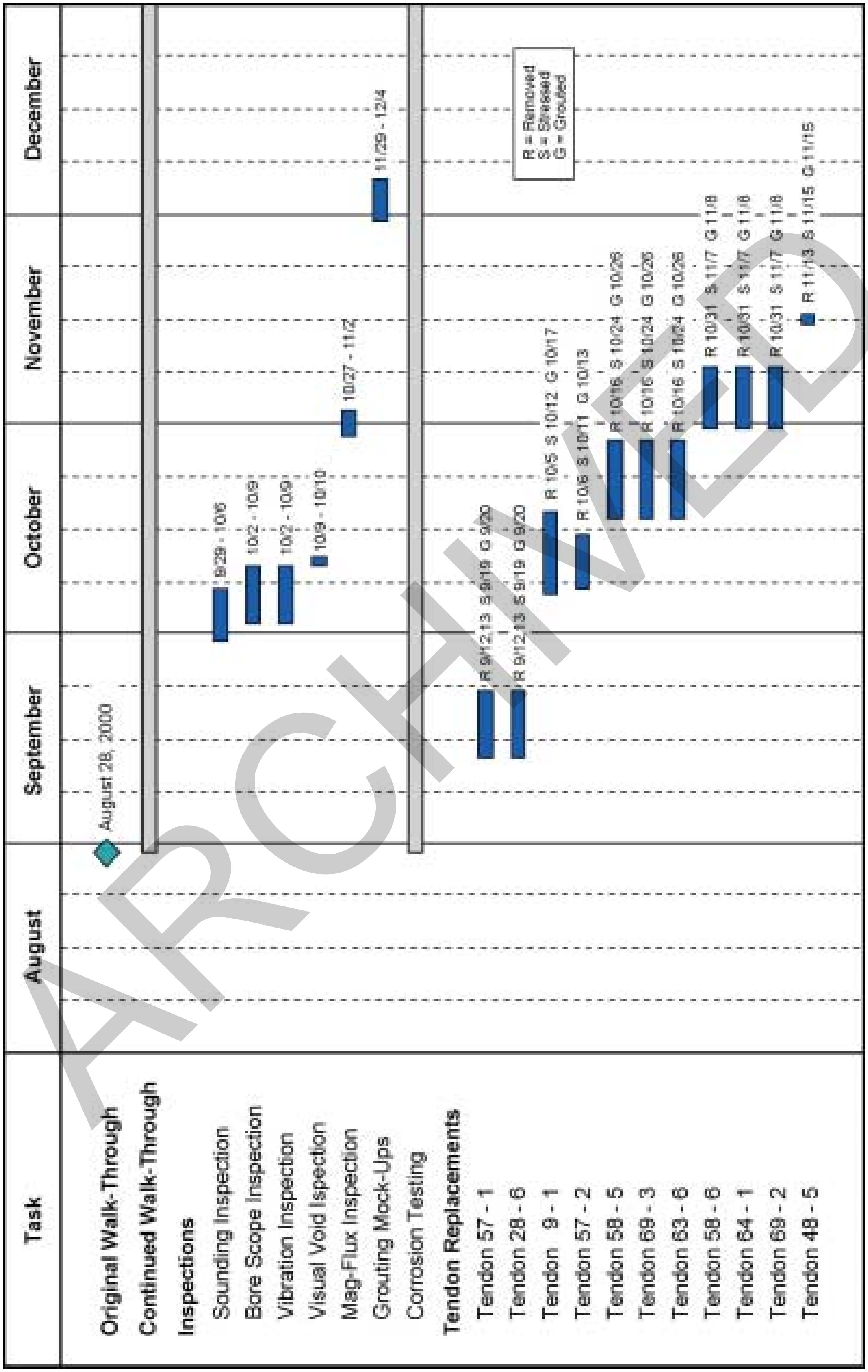


Figure 1.5 – Schedule of Inspection and Repair Activities for the Mid-Bay Bridge

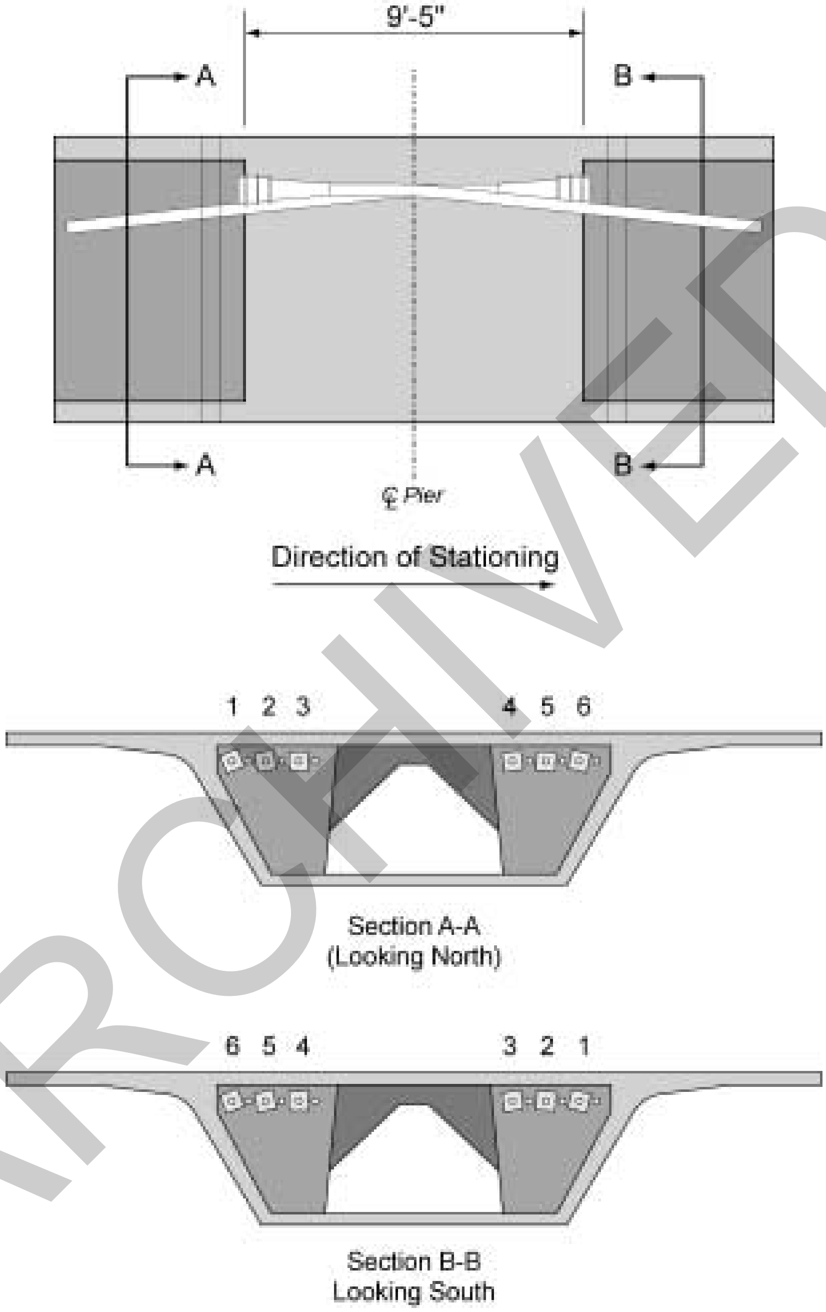


Figure 1.6 – Tendon Numbering Convention (Interior Piers)

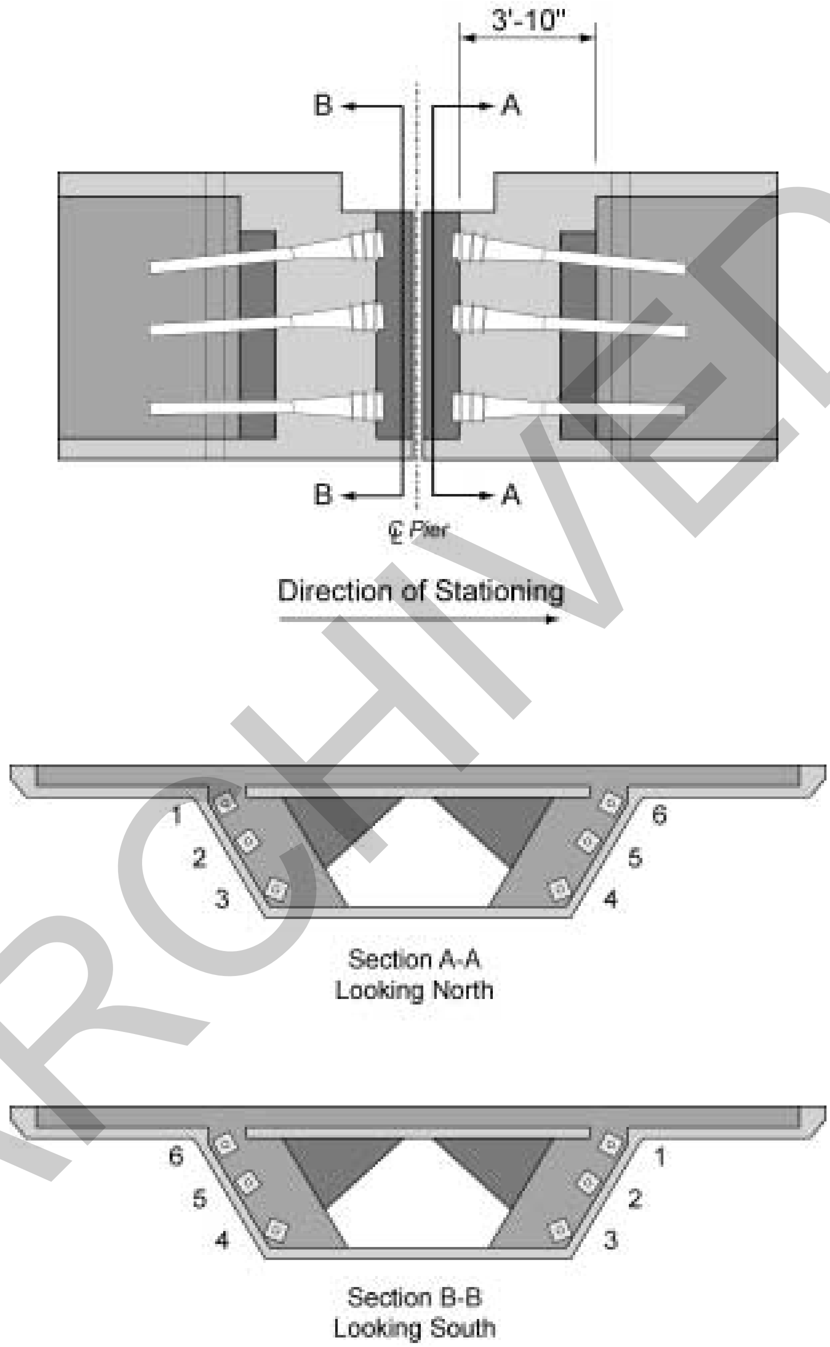


Figure 1.7 – Tendon Numbering Convention (Expansion Joint Piers)

Chapter 2 – Inspection And Testing

2.1 Introduction

The post-tensioning system of the Mid-Bay Bridge has undergone a rigorous inspection and testing regiment since the discovery of failed external post-tensioning tendons. FDOT and consultant inspection personnel have worked systematically and aggressively to catalog the condition of the bridge's post-tensioning system. The major inspections and tests conducted were:

- Sounding Post-Tensioning Tendons for Voids
- Bore Scope Inspections of Post-Tensioning Anchors
- Vibration Testing
- Visual Void Inspections
- Mag-Flux Testing
- Grouting Mock-Up Tests
- Other Corrosion Related Testing

No one inspection or testing procedure is able to provide a complete evaluation of the corrosion of external post-tensioning tendons. Tests that give good results in the free length of external tendons do not give any results in the anchorage zones. Tests that give strong indications of active corrosion in a length of tendon do not necessarily predict the level of force in the tendon or section loss that has occurred. The proper approach for inspecting external post-tensioning tendons is to conduct a battery of tests specifically chosen to develop an understanding of the tendon conditions. This was effectively accomplished for the Mid-Bay Bridge.

This chapter summarizes the testing and inspection of the post-tensioning system of the Mid-Bay Bridge. More complete results and raw data of these inspections and tests are provided in the Appendices to this report.

2.2 Sounding Post-Tensioning Tendons For Voids

Examination of the two failed tendons, one in Span 28 and one in Span 57 revealed that the condition of the grout for these tendons was suspect. Air cavities, bleed water trails and soft, chalky grout characteristics were observed. Significant voids in grout or a highly porous grout can reduce the corrosion protective capabilities of this system. For this reason, a program of sounding the tendons for voids was initiated. In this procedure, an inspector walks the length of each tendon tapping lightly with a small tack hammer, listening for changes in the resulting sound. Locations of variations in sound that would imply a void are recorded. Locations where significant variations in sound are found are then evaluated for the need of a visual inspection. Visual inspection includes removing a portion of the polyethylene duct and visually inspecting the prestressing strands and surrounding grout.

The field notes of the sounding testing for the Mid-Bay Bridge are found in Appendix A. These results show that there is a consistent presence of voids in the tendons. These voids appear to be a mixture of air entrapped during grouting, expansive gasses, and bleed water trails. Figure 2.1 shows a large void found in Tendon 37-4. The sounding tests did not identify any significant distress in the post-tensioning tendons. The conclusion of the inspection teams was that this method of inspection is very unproductive and should not be a part of future condition inspections. A slight delamination between the polyethylene pipe and grout caused by grout subsidence and shrinkage can produce test results indicating voids are present even though the duct is full. The subsequent opening of the polyethylene duct and exposure of the prestressing strands to the humid atmosphere can do more harm to the system than good. Furthermore, it requires a wrapping of the duct immediately after the inspection.

Figure 2.1 – Bleed water trail found by sounding inspection.

2.3 Bore Scope Inspections

The failure of Tendon 57-1 (see Chapter 3 – Tendon Replacement) resulted from the corrosion of the prestressing strands in the tendon inside of the post-tensioning anchorage assembly. Removal of this tendon indicated that there was no grout inside of the anchor head. At the time of inspection, the assembly was found to be in a dry condition. Therefore, it is believed that water was present at the time of construction and caused the corrosion. As a result of this finding, an inspection procedure was developed using flexible bore scopes to video record the interior of all anchor heads that contained voids. The inspection would determine whether sufficient grout was present in each anchor and the extent of corrosion on exposed post-tensioning tendons.

Figure 2.2 shows a typical anchorage assembly for the post-tensioning system used in the Mid-Bay Bridge. The anchorages used on the Mid-Bay Bridge hold 19 strands; the anchor shown in Figure 2.2 holds 12 strands. This cutaway view shows the cast metal multi-plane anchorage, the prestressing strands inside the anchorage, and the anchor plate used to hold the prestressing strands after stressing through the aid of wedges. The grout port is the smaller threaded hole at the top of the multi-plane anchorage.

In the typical grouting operation of the Mid-Bay Bridge, the grout was injected through the grout port in the anchor at one end of the tendon. The grout is continuously placed until the duct between the anchors is filled with grout and grout is flowing from the grout port at the end of the tendon and out of the vent port on both duct anchorage caps. This will assure no air lock has occurred in the bottom of the anchorage at the time of lock-off. The voids that are present in the Mid-Bay Bridge are inside the anchor, just behind the anchor plate, extending variable distances along the length of the tendon.

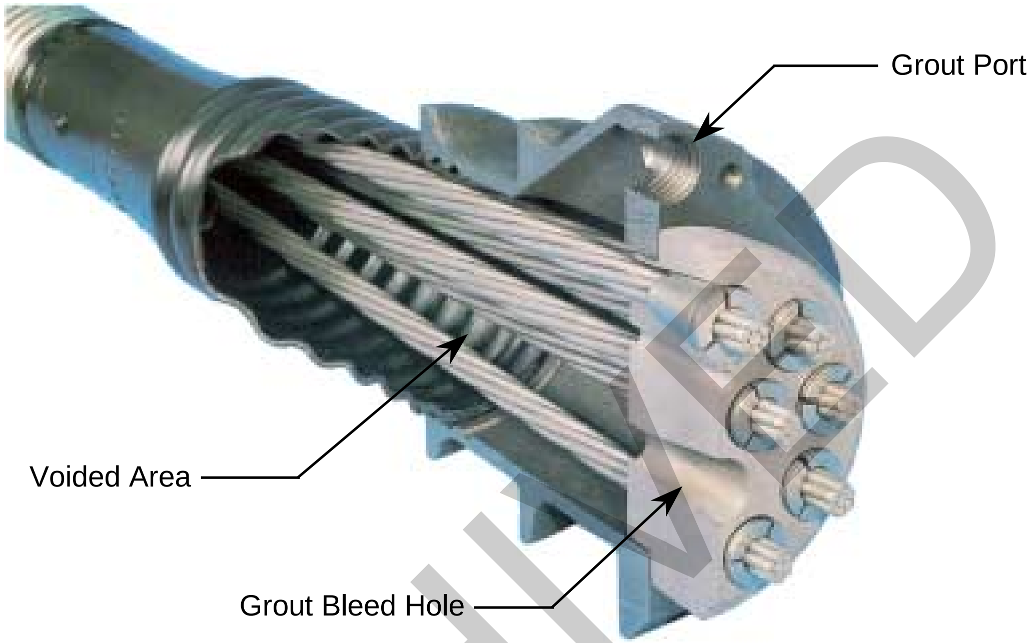


Figure 2.2 – Typical Post-tensioning tendon anchor.

Four, four-person crews were used to inspect post-tensioning anchorages throughout the bridge. The bore scope is inserted in to the grout port after the grout filling the port is drilled out. Drilling is required for 2” to 3” before the clear access is available into a voided trumpet. If grout was found after drilling 4” then the anchorage was generally full. One inspector manipulates the bore scope inside of the anchorage while another inspector controls the video equipment. The other two members of the team provide support services to the two inspectors, including a hand written log documenting the number of strands viewed, depth of void, extent of corrosion and whether or not a second bore scope inspection was in order. All tendons that received a second inspection were reviewed by the lead inspector to have a consistent perspective as the extent of corrosion. Figure 2.3 shows a bore scope team inspecting an anchorage of the Mid-Bay Bridge. The inset photograph in Figure 2.3 shows the bore scope as it is inserted into the grout port.

The results of the bore scope investigations are still photographic captures and videotapes of each anchor head and field notes indicating the condition of the strands and grout inside the anchor. The field logs of the bore scope inspections are included in Appendix B to this report. Video results of the inspections are in the District 3 office of FDOT. Further information on the results of bore scope inspection of the over 1700 anchorages can be found in Appendix B.

Figure 2.4 shows four photographic still captures of bore scope inspections of different anchorages. These photographs show four typical conditions that were found in the anchor heads of the Mid-Bay Bridge. Clockwise from the upper left, the anchor conditions are:

- Tendon 104-2, North Anchor: Small void, no strands exposed.
- Tendon 14-3, North Anchor: Large void, strands visible with thin grout coating (moon dust)
- Tendon 59-1, North Anchor: Large void, strands visible with little corrosion
- Tendon 48-5, North Anchor: No grout, heavy corrosion, broken wires

Figure 2.3 – Bore Scoping a Post-Tensioning Tendon Anchor Head

Figure 2.4 – Still photographic captures from Bore Scoping Inspections.

2.4 Vibration Testing

Vibration Testing of the post-tensioning tendons was conducted by A. A. Sagues, P.E., PhD., of the University of South Florida. Initial vibration testing was performed on the remaining five tendons of both Spans 28 and 57 on the evening of August 28, 2000 and early morning of August 29, 2000. The results of this testing gave initial confidence to re-open the bridge to two-axle vehicular traffic. Bore scope inspections (Section 2.3) of the anchorages of these tendons provided FDOT engineers with additional information that subsequently disallowed the vibration testing as the sole source of evaluation of the post-tensioning tendons (See discussion in the last paragraph of this Section).

Complete vibration testing of all tendons was conducted from October 2, 2000 to October 9, 2000. This testing consisted of measuring the vibrational response of tendons to mechanical excitation, and using the results to estimate the force in the tendons. Comparison of results for the various tendons in the bridge can be used as a possible indicator that a tendon may be in distress.

The vibration testing begins by manually striking the tendons with a hammer, and recording the resulting vibrations for later analysis. A "dead-blow" hammer was used, hitting perpendicular to the tendon axis. The head of this type of hammer contains metallic shot in a yielding plastic enclosure, thereby minimizing damage to the polyethylene tendon duct and reducing the chances for multiple bouncing impacts.

Each tendon was tested in each of its three free lengths: from the south diaphragm to the deviation beam (Zone A), from deviation beam to deviation beam (Zone B), and from deviation beam to north diaphragm (Zone C). The impact point was at a distance of 1/6 of the free length from the end of the zone being tested. A single axis accelerometer was attached temporarily with wax to the polyethylene duct at a point distance of 1/3 of the free length from the end of the zone being tested. The accelerometer axis was normally parallel to the direction of the hammer blow, so that in-plane vibrational modes would be detected.

Signal recording was performed using a laptop computer and proprietary software to acquire stereo audio input. The software creates an audio file (*.wav) of the recording that is stored in the computer hard drive, and provides visual indication of the waveform and spectral distribution obtained, allowing for immediate feedback in case a test needed to be repeated. Another proprietary computer program is used to compute the tension in the tendon. Figure 2.5 shows photographs of the vibration testing and the visual display of a tendon test.

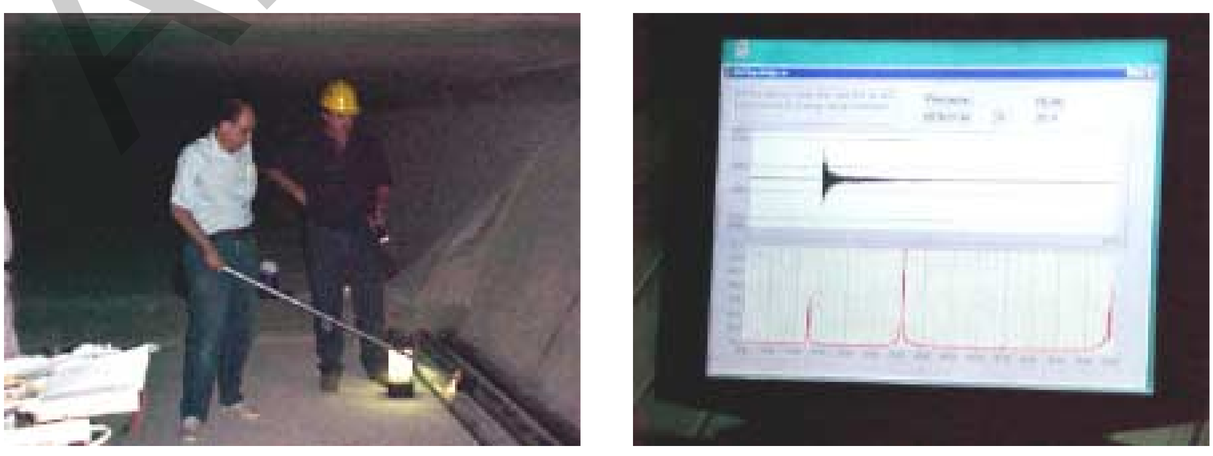


Figure 2.5 – Vibration Testing

The raw data and synthesized results of the vibration testing for the Mid-Bay Bridge post-tensioning tendons is presented in Appendix C to this report. Figure 2.6 shows a summary plot comparing the stresses in Zone A and Zone C of the tendons. Equal forces in the two zones would result in a point plotted on the 45° line. The variations of all of the tendons are essentially within a +/-6% variation from equal values, indicating no significant loss in forces along the length of the tendon. Some variation is expected to exist as a result of friction developed during the stressing of the tendons.

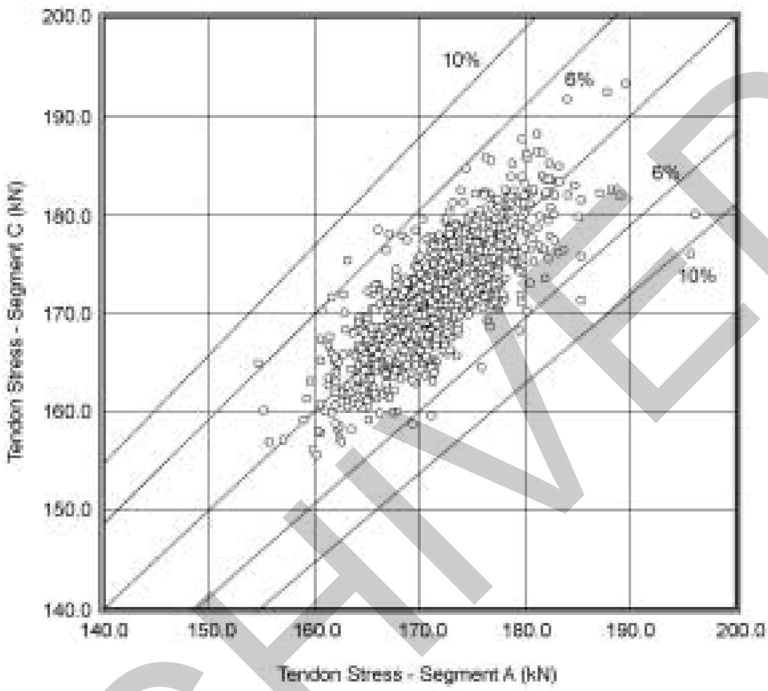


Figure 2.6 – Comparative tendons forces from vibration testing.

The vibration testing of Tendon 9-1 gave an indication that force had been lost in one portion of the tendon. Figure 2.7 shows the results for all tendons in Span 9. This bar chart shows a drop in the force in Tendon 9-1 between the deviation diaphragm and the expansion joint pier segment. Bore scope review of this anchor gave indications of heavy corrosion and wire breaks at this end of the tendon.

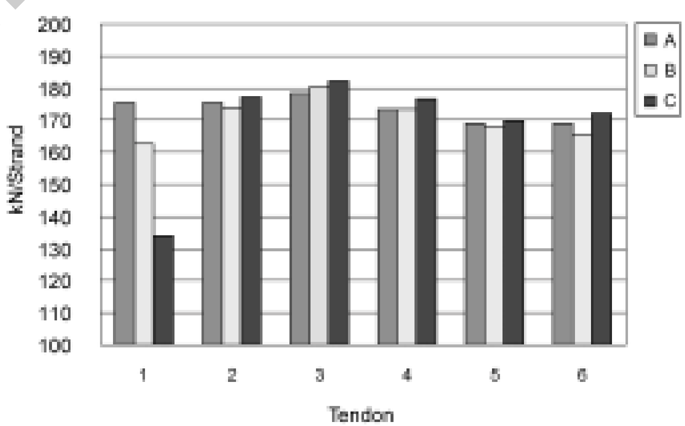


Figure 2.7 – Vibration results for Span 9

The vibration testing of post-tensioning has distinct limitations. The results may not be true for the entire length of tendon if grout in the pier segment duct and/or trumpet bonds the tendon significantly. This might give indications of a good tendon without knowledge of strand conditions in the anchor (see Figure 3.2 in Section 3.1). The analytical assumptions used in data reduction are very subjective and may not be valid if end fixity, duct condition, and grout mass vary. The absolute values of this type of vibration testing should be used cautiously. The results shown in Figure 2.7 indicate relative differentials between Segments A, B, and C for Tendon 1 in Span 9, and are cause for further investigation.

2.5 Visual Void Inspections

Several visual inspections were made of areas in the free length of the post-tensioning tendons of the Mid-Bay Bridge. These inspections were performed by stripping portions of the polyethylene duct in the vicinity of an area believed to be experiencing corrosion. These areas were located during the sounding inspections, mag-flux inspection or as an observation during the initial walk-through inspection of an obvious defect in a duct. Several of these locations were found to be locations where corrosion had taken place or was ongoing. Figure 2.8 shows a stripped portion of Tendon 40-2. When this area was first stripped the grout was found to be very fractured and chalky to the touch. Two wires in one of the seven-wire strands were broken. Two other wires in the same strand broke as additional grout was removed from the section. The portion of the tendon was marked for future patching and wrapping. Further implications of this type of duct defect are discussed in Chapter 3, Section 3.6 and Chapter 4, Section 4.3.

Figure 2.8 – Tendon 40-2, corrosion in the free length of tendon.

2.6 Mag-Flux Testing

Mag-flux Testing of the post-tensioning tendons of the Mid-Bay Bridge was conducted by Dr. A Ghorbanpoor, Ph.D., P.E., of the University of Wisconsin-Milwaukee. The on-site testing was performed from October 27, 2000 to November 2, 2000. Mag-Flux testing uses the concept of magnetic flux leakage to give a non-destructive evaluation of cross section loss of post-tensioning tendons. An area in close vicinity to a post-tensioning tendon is subjected to an induced magnetic field. Changes measured in the magnetic field can be correlated, based on previously performed calibrations, to steel section loss due to corrosion or wire breakage.

The equipment used in Mag-Flux testing consists of a mechanical frame that supports a pair of strong permanent magnets and a series of magnetic field sensors. The data received from the magnet/sensor assembly is collected by data acquisition software on a laptop computer to facilitate data recording, displaying and interpretation. The magnet/sensor assembly rides along the free length of the external post-tensioning tendons on a set of contact wheels. The contact wheels maintain a constant distance of 0.25 inches between the face of the magnet/sensor assembly and the surface of the polyethylene duct of the post-tensioning tendon.

Testing of the post-tensioning tendons of the Mid-Bay Bridge consisted of placing the magnet/sensors assembly of the test machine on the three free lengths of each tendon (from pier diaphragm to deviation beam, from deviation beam to deviation beam, and from deviation beam to pier diaphragm). The magnet/sensor assembly is then moved with a steady motion along the fee length of tendon. Magnetic flux leakage data from the tests were transmitted to the computer and recorded. The synthesized data was displayed back to the investigator in the form of real time plots from the different sensors on the test machine. The investigator was able to evaluate the real time plot and note the location along the length of the tendon where section loss from corrosion or wire breakage occurred. Figure 2.9 shows the max-flux testing operation.

A more complete presentation of the Mag-Flux testing procedure can be found in the Final Report *"Condition Assessment of External P-T Tendons in the Mid Bay Bridge"* prepared by Dr. Ghorbanpoor. This report is reproduced in Appendix D to this report entitled "*Mag-Flux Test Results."*

Figure 2.9 – Mag-Flux Testing

Mag-Flux Testing of the Mid-Bay Bridge found two locations along the lengths of two post-tensioning tendons where the results indicated corrosion and section loss had occurred. These locations and the findings were:

- Tendon 71-1 produced a positive test result for possible section loss in Segment A of the tendon, 30' from the start of the test. Physical examination of this location found a small hole present in the polyethylene duct. A small window was cut in the duct to further determine the extent of the corrosion. Four wires of a seven-wire strand were heavily corroded just below the surface of the hole in the duct (See photograph in Appendix D). This was not considered severe enough for replacement of the tendon. The duct was sealed following inspection.

- Tendon 98-5 produced a positive test result for possible section loss in Segment C of the tendon, from 9’ to 10.5’ from the start of the test. Physical examination of this location found another small hole in the polyethylene duct. A small window was cut at this location of the tendon and heavy corrosion limited to the four wires of a seven-wire strand was found (See photograph in Appendix D). This was not considered severe enough for replacement of the tendon. The duct was sealed following inspection.

Mag-Flux testing of external post-tensioning tendons has limitations. The testing procedure is only able to locate a place in the tendon where corrosion has occurred, but the extent of the section loss is not known without physical examination of the tendon. The testing procedure is also very sensitive to any variations in the position of the magnet/sensor assembly relative to the tendon. Imperfections on the surface of the tendon or previous repairs in the form of wrappings can change the distance from test equipment to the tendon and produce poor results. Mag-Flux testing gives no indication of voids in the grout or bleed-water pockets. As a result, Mag-Flux testing cannot be used to find possible locations of future corrosion. Mag-Flux testing is best used in this application to find and seal duct defects that have lead to corrosion so that further deterioration can be avoided.

The Mag-Flux testing did again draw attention to a construction and inspection practice that lead to unnecessary corrosion of external post-tensioning tendons. Often, during grouting and subsequent inspection of the grouted tendons at the time of construction, the tendons will be sounded to determine if there might be voids in the grout. When a possible location is found, a small nail will be tapped into the duct to verify the presence of grout. Holes left open after this inspection provide localized entry locations for warm, humid air and the opportunity for localized corrosion of the tendons. This same type of corrosion cell has been found in other post-tensioned bridges in Florida and may have been the cause the failure of Tendon 28-6, which is presented in Chapter 3, Section 3.1. The dry joints on this bridge have efflorescence which is evidence of slight water leakage that may be contributing to the humidity which charges these slow growing corrosion cells. Utility owners should also be trained not to nick or damage duct material.

In general, the number of tendon corrosion locations detected by Mag-Flux testing, was very low considering the number of tendons in the bridge. However, many of the ducts that had already been sealed by heat wrapping could not be successfully tested for reasons stated above.

2.7 Mock-Up and Field Trial For Filling Voids In Anchorages

A significant feature of the rehabilitation of the post-tensioning system of the Mid-Bay Bridge is the filling of voids behind anchor heads with grout. Different grout materials and placement methods were developed with a goal of producing an approach that builds high confidence in the long-term integrity of the anchorages.

The grout chosen for the repair was Master Builders 816 Cable Grout. This cementitious grout meets the requirements of the interim grouting specifications currently being used by FDOT. Two methods seemed most viable for placing the grout in the anchor head voids. These two methods were:

- Pressure Injection - Placement of grout under positive pressure through a straw inserted through the grout port, deep into the void and retracted as the void is filled.
- Vacuum Injection - Placement of the grout under a vacuum produced by drawing the air out of the void. The negative pressure is used to draw the grout into the anchor head.

Mock-up testing using the two proposed methods of grout injection was conducted to determine which produced the most effective repair of the anchor head. The mock-up tests were performed using the same components of the post-tensioning system used in the Mid-Bay Bridge. Post-tensioning strands were placed inside of anchor head and duct and partially filled with grout. The mock-up tests were slightly inclined to replicate voided conditions similar to those found during the bore scope inspections. Figure 2.10 shows the mock-up test specimens.

Figure 2.10 – Mock-up test specimen

After the grout in the test specimen hardened, the two different methods of injection, positive pressure and vacuum injection, were used to fill the voids in the anchor heads. Figure 2.11 shows the two injection methods in progress. The positive pressure method is shown on the left with the straw inserted into the grout port of the anchor head and a hand pump being used to force the grout into the voids. The vacuum injection method is shown at the right in Figure 2.11. One end of the grout injection tube is connected to the grout port. The other end is attached to a switchable manifold. The air is first removed under vacuum, being drawn out by the grout-metering pump. The volume is measured on the vacuum and therefore provides an estimate and degree of confidence in the amount of grout to be placed. Generally the amount of grout placed in the Mid-Bay Bridge has been slightly higher volume than the vacuum indicated. In the second stage of work the manifold controls are switched, locking off the vacuum and allowing the grout to be pulled into the void.

Figure 2.11 – Injection methods: Positive Pressure (left), Vacuum Injection (right).

Following the injection and hardening of the grout, the test specimens were cut into sections along the length of the tendon. These sections were reviewed to determine the efficiency of the two grout injection methods. Figure 2.12 shows a section of specimen injected under positive pressure on the left, and a section of a specimen injected under a vacuum on the right. The results of the tests indicated that the vacuum injection method better filled the voids in the mock-up samples. The specimens injected under a positive pressure were found to have voids, as shown at the left in Figure 2.12, or to have clearly defined interfaces between the new and old grout. Voids were not present in the tendons injected under a vacuum and there was a consistent flow of the grout into the voids and around the annular spaces inside the duct (note the extent of the lighter colored grout at the top of Figure 2.12 on the right).

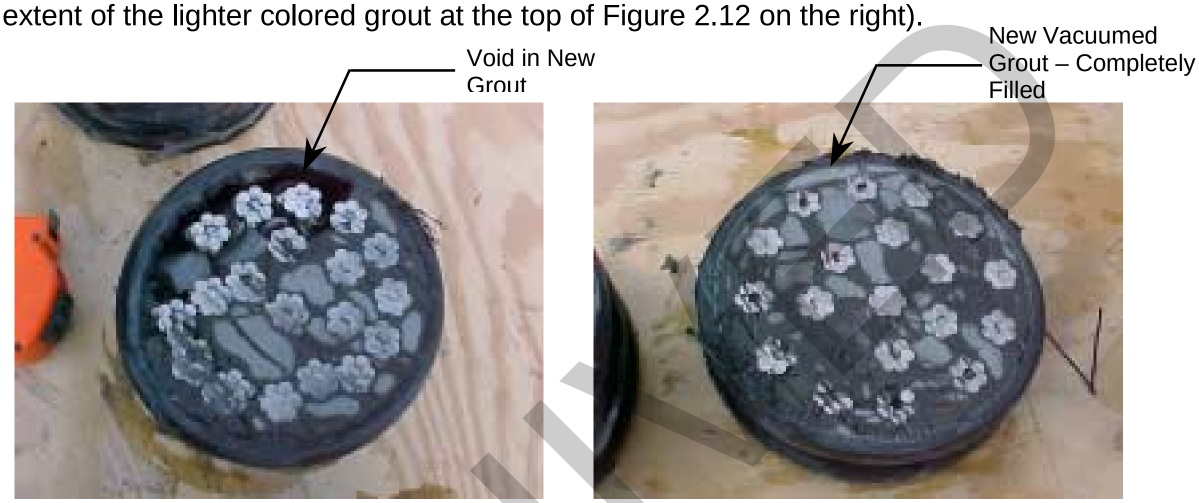


Figure 2.12 – Mock-up tests segments: pressure injection (left) and vacuum Injection (right).

Following the mock-up testing a field trial was conducted to determine how to use the vacuum method of injection in the rehabilitation of the Mid-Bay Bridge. The photographs in Figure 2.13 show different scenes during the field trial. The photograph on at the bottom right of Figure 2.13 shows the finished grout cap this tendon. Based on the mock-up testing and field trials, the vacuum method of injecting the voids behind the anchors in the Mid-Bay Bridge is being used.

Figure 2.13 – Field trial of the vacuum injection method.

2.8 Other Related Testing

Several other tests were performed on the components of the post-tensioning system of the Mid-Bay Bridge in order to evaluate their adequacy with regard to providing resistance to corrosion protection. The results of these tests are presented in this section. Back-up information regarding these tests can be found in Appendix D entitled *"Other Related Testing."*

2.8.1 Polyethylene Duct Testing

Two different testing laboratories were asked to test different characteristics of the polyethylene duct used on the Mid-Bay Bridge. Polyethylene has the characteristic that samples can be melted and reconstituted into testing samples while maintaining its physical properties.

Hancor, Inc. (Hancor) was asked to evaluate the duct for conformance to ASTM D 3350 cell class 345433C. This was the ASTM testing procedure and cell class called for in the project specifications. Four of the tested characteristics (density, melt index, flex modulus and tensile strength) met the ASTM requirements. The duct material did not meet the test requirements for the Environmental Stress Crack Resistance (ESCR). The ASTM requirement is that not more than a 20% specimen failure is permitted over the 192 hour test duration. The tests performed by Hancor for the duct for the Mid-Bay Bridge exhibited 100% failure to the test in less than 24 hours.

Atofina Petrochemicals, Inc. (Atofina) was asked to perform chemical and rheological testing on the polyethylene duct of the Mid-Bay Bridge. The chemical testing results indicate that the percent of carbon black in the post-tensioning ducts was 1.2% and that the density of the material was higher than expected. The ASTM requirement for carbon black content in this material is a minimum of 2%. The rheological tests indicated that the base resin appears to be a medium molecular weight grade lower than commonly used in pressurized pipes. The Atofina tests state that the combination of high density and low molecular weight will produce a product with high brittleness.

These two brief reports are included in Appendix D and should be further investigated by the bridge authority. The construction material apparently did not meet the requirements of the construction specifications and this could be a source of duct cracking. Additional studies are underway which may identify likely mechanisms for duct cracking.

2.8.2 Grout Testing

The FDOT State Materials Office in Gainesville, Florida performed many tests to evaluate the chemical characteristics of the grout of the Mid-Bay Bridge. A sample of the results of one of these tests for the grout in Tendon 40-2 is provided in Appendix D of this report. The FDOT State Materials Office has consistently found the pH values of the grout to be appropriate and the chloride content to be on the order of 0.25 pounds of chloride per cubic yard of grout. This chloride content is a trace amount consistent with expected values for cement-based materials.

SKW/MBT, Inc. (SKW/MBT) of Cleveland, Ohio was asked to perform chemical and petrographic examinations of samples of the grout of the Mid-Bay Bridge. Specifically, SKW/MBT was asked to determine if grout expansion could have caused the cracking of the polyethylene duct. The results of the tests by SKW/MBT did not indicate that there were any unusual conditions that would have led to unexpected expansion. The testing did indicate that the water cement ratio of the grout was very high and that the variation in the grout characteristics from the surfaces formed by the ducts inward towards the strands indicated a significant migration of bleed water. (See Appendix D)

2.8.3 Prestressing Steel Testing

Samples of the corroded prestressing strand of Tendon 57-2 were tested for tensile strength by the FDOT Structures Research Center. The results of these tests indicated that strand pitted to the extent of this tendon had a reduction in ultimate strength of 12%. This reduction was determined by comparative testing of other portions of the failed tendons that were not corroded (See Appendix D).

The level of corrosion on the portion of Tendon 57-2 that was tested was representative of several locations on several tendons in the bridge. It was not representative, however, of some of the more severely corroded locations. These more severely corroded locations occur near the end of the tendon where there was insufficient length of strand for the testing equipment to grip.

2.8.4 Tendon Potential Testing

The prospect of re-injecting voided anchors with new grout gave concern that the water in the new grout could add to the corrosion of the prestressing steel in the post-tensioning tendons of the Mid-Bay Bridge. The FDOT Materials Laboratory developed a testing procedure to measure the change in electrical potential within the grout as it cures. This testing was performed in conjunction with the field trials of the vacuum grouting of anchors. The results of the testing indicate that the potentials stabilize and the water in the grout is consumed in the hydration of cement and drying of the grout. The results of these tests are presented in a report entitled *"Mid-Bay Bridge Tendon Potential Test"* found in Appendix D.

Chapter 3 - Findings Of The Inspection And Testing Program

3.1 Failed Post-Tensioning Tendons

The first tendon, Tendon 28–6, was discovered partially failed on August 28, 2000 during a regularly scheduled FDOT annual inspection of the Mid-Bay Bridge (one of two inspections the bridge receives each year). The inspectors found the duct at this location to be significantly cracked and bulging. Figure 3.1 shows that the corrosion of Tendon 28-6 in the free length of the tendon between a deviation diaphragm and expansion joint pier segment diaphragm after the duct had been cut away. Damage to the duct after strand failure did not permit the evaluation of whether damage to the duct prior to strand failure led to the localized corrosion of the tendon.

Figure 3.1 – Tendon 28-6

An immediate walk-through inspection of the Mid-Bay Bridge was conducted after finding the damage to Tendon 28-6. This inspection found that Tendon 57-1 had completely failed. This was evidenced by the complete pull out of the tendon and embedded steel duct from the expansion joint diaphragm. The failure of Tendon 57-1 is shown in Figure 3.2.

Figure 3.2 – Tendon 57-1

The corrosion of the prestressing steel in the anchor produced a loss in cross sectional area that caused strands to fail. The force from these failed strands was then restrained through the bond with the steel duct and the unbroken strands through the grout that was present in the duct. The load in the steel pipe was transferred to the surrounding concrete and the force in the remaining intact strands was carried back to the anchor head. The rigidity of the diaphragm concrete versus the remaining strands would force the majority of the load into the steel pipe and surrounding concrete. Eventually the corrosion and breaking of the strands was sufficient to exceed any resistance provided by the few remaining prestressing strands and all the load was transferred to the steel duct/concrete interface. This bond between the rigid duct and the diaphragm concrete then failed allowing the tendon to slip into the span.

Post-mortem inspection of the strands in the anchor head of Tendon 57-1 revealed that the wires not fractured as a result of corrosion were necked-down indicating sudden failure with additional transfer of load to the steel duct. This was consistent with the failure mode described above.

Post-tensioning anchorages are designed to transfer prestressing loads from the strand, through the wedges, to anchor plate, and then to the bearing surfaces of the anchorage. Though not considered in the design of the anchorage itself, the analysis, testing and approval of post-tensioning systems all consider complete grouting. It is clear that the tendons of the Mid-Bay Bridge are not constructed with grout to the same details as used during the development and approval of the post-tensioning system. The consequence of the difference will be investigated further by FDOT in the months to come.

Figure 3.3 shows two other photographs of the failed Tendon 57-1. The photograph on the left shows the anchor head after removal from the anchorage. The majority of the strands are still held in the anchor head by the wedges. The extent of the corrosion and the nature of the corrosion-induced breaks are evident. The photograph on the right of Figure 3.3 shows the extent of the corrosion inside of the multi-plane anchor casting. This photograph also gives evidence that the water contributing to corrosion was locked in place in the anchor during construction. The protective epoxy coating and black mastic seal was completely intact at the time of the discovery of the failed tendon. The light gray circumferential break, shown completely around the anchor, is the epoxy layer of the anchor protective coating.

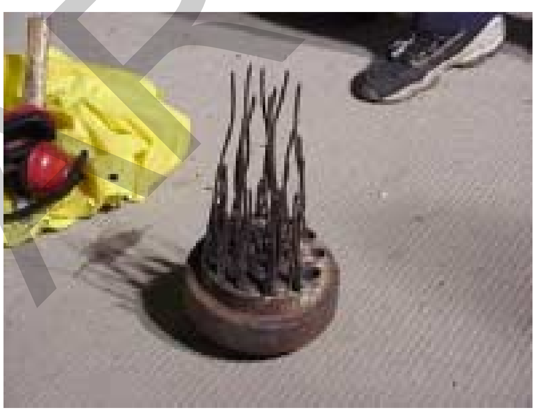



Figure 3.3 – Anchor Head and Anchor of Tendon 57-1

Tendon 28-6 and Tendon 57-1 are the only tendons that had experienced failure. Each one had failed because of a loss in cross sectional area due to corrosion. Tendon 57-1 failed in the anchor just behind the anchor head. The other tendon (Tendon 28-6) failed in the free length of tendon. Both of the tendons were located in expansion joint spans and both were the most highly draped tendons in the spans. Later inspections confirmed the majority of voids and corrosion occurred in the most highly draped tendons.

3.2 Voids In Post-Tensioning Anchors

Review of the failure of Tendon 57-1 showed little or no grout in the anchorage immediately behind the anchor head at the expansion joint end of the span. Based on this information, the ten other anchors of this span were bore scoped as described in Section 2.3 of Chapter 2 in this report. Each of the anchorages scoped at this time showed significant voids in the anchors and corroded strands.

Engineers are aware that small voids can occur in post-tensioned concrete construction. The acceptability of voids is influenced by factors such as: exposure and condition of strands, condition of grout, possible paths of recharging, relative structural significance of the tendon, and surrounding environment. Voids that leave the strands susceptible to attack from corrosion are not acceptable and require filling. The Florida Department of Transportation, considering factors similar to those just listed, used engineering judgment to decide that no known void in an anchorage would be acceptable in the Mid-Bay Bridge. All voids would be filled with grout using the vacuum injection techniques described in Chapter 2.

The presence of the voids and corrosion in the post-tensioning tendons most likely resulted from one, or a combination of, the following items:

- Contamination – Water entering an ungrouted tendon before or after tendon stressing. This water can be in the form of water used to flush the ducts, deck runoff or humidity of the surrounding air. The air in the area of the Mid-Bay Bridge has suspended salt spray and may have carried chlorides into the duct system.
- Leakage of grout – "Blow outs" of the grout at the neoprene boot connections between steel and polyethylene can lead to a loss of grout.
- Excessive bleed water – Free water moving to the tendon high points allows the remaining grout to settle back into the duct away from the anchor. This can be aggravated by excessive water in grout.
- Subsidence of the grout – Grout in tendons that are filled from a high point can cavitate and capture air in the grout column. Before the initial setting of the grout the captured air or gas from expansive agents rises to the high point, in this case inside the anchors behind the anchor heads.
- Settlement – gravity induced separation of cement from the water in the grout mix.
- Recharge – Deck runoff may flow over the anchorages after grouting and before expansion joint installation. The porous grout without its pour-back and mastic may absorb water. This has been documented on another Florida post-tensioned bridge anchorage in a vertical application. Another potential for recharge and continued strand corrosion is through a separation between a pour-back and bulkhead. Most anchorages on the Mid-Bay Bridge did not have a pour-back and therefore the void may have been exposed to recharge prior to the re-grouting of the cap and/or mastic installation.

It is interesting to remember that the most significant voids in the ducts of the Mid-Bay Bridge were at the expansion joint diaphragms. Given an amount of bleed water and cavitation, the total volume of the void at either end of the tendon should be nearly the same. At the interior pier segments this volume would be distributed over the horizontal tendon profile resulting in long but thin voids that would not expose strands. At the expansion joint pier segments the voids would collect at the tendon high point just behind the anchor head and would be shorter and deeper, exposing strand. The change in inclination of the expansion joint span tendons as they anchor at the expansion joint diaphragms would produce deeper voids in tendons 1 and 6 and shallower voids in tendons 3 and 4. All of these tendencies were found to be consistently present in the Mid-Bay Bridge as revealed by the bore scope inspections.

3.3 Grout Quality

The general impression of the inspectors and investigators involved with the review of the Mid-Bay Bridge is that the grout is of suspect quality in many areas of the bridge. Samples taken and tested were described as soft, chalky and visibly porous. The nature of the components of the grout along with the admixtures is currently being chemically analyzed for project specification compliance. The water/cement ratio and expansive agent content of this grout may not have been correct. The petrographic investigations found that the grout was poorly mixed, in that un-hydrated cement particles were found near the outer perimeter of the tendons. This allowed the excess bleed water to migrate upward through the grout near the strands. This is consistent with the findings where bleed-water migrated upward into the tendon anchorages, thus creating or adding to the voids in the anchorages after some period of time.

Another indication of the quality of the grout can be color. The traditional color of well proportioned and cured grout in Florida is light gray. Much of the grout in the tendons requiring replacement in the Mid-Bay Bridge was white indicating high water content and grout segregation. The significant variation in color of the grout from the top of the duct (white) to the bottom of the duct (darker gray) was further indication of a higher than normal water content. Much of the pour-back grout in the Mid-Bay Bridge grout caps has a dark gray color with visible silica. This grout was either poured or packed into the grout caps and did not flow into the trumpet area through the wedge plate. The shortfall is that the void is locked in place, since this secondary material just covered the anchor head.

Figure 3.4 shows two views of dark gray grout at anchors of the Mid-Bay Bridge. The photograph on the left shows the dark gray grout used as a pour-back to fill the cap during construction, leaving a partially voided trumpet. The light colored grout in this photograph comes through the grout bleed hole into the cap during grouting. Caps with subsidence or partial fill were consistently found to be indicative of a partially filled trumpet. The photograph on the right shows the dark gray grout throughout the anchor.

Figure 3.4 – Dark Gray Grout

3.4 Cracking Of Polyethylene Duct

There is substantial cracking of the ducts on the Mid-Bay Bridge. This is not a new issue found in association with the recent studies of the bridge. Cracking of the duct has been observed since the bridge has been opened and protective wrappings have been applied in a previous maintenance contract (1997). More extensive cracking has occurred since these maintenance operations.

The polyethylene duct was tested to see if the characteristics of the duct were appropriate for this application. The results of these tests indicate that the duct did not meet the requirements of ASTM D 3550 and cell classification as called for in the project specifications. Further testing indicated that the high density and medium molecular weight grade of the resin would produce a brittle polyethylene that perhaps should not be used in these type applications. This is further compounded by radial stresses in the duct induced during grouting that can reduce duct durability.

3.5 Protection of Post-Tensioning Anchorages

Visual and random sounding inspections of the protective coatings of the anchorages in the Mid-Bay Bridge were conducted. The visual damage found consists of cracking and/or spalling of the coal tar epoxy coating. Sounding results indicated a hollow sound at many locations where there was no visible external damage to the protective coatings. Removal of these intact protective coatings typically revealed a mix of white and sandy gray grout in the grout cap. Locations with hollow sounding, intact protective coatings also had voids anchorages and corrosion on the strands and anchor plates. These findings would indicate that some locations of failed protective coatings are the result of the expansion of the steel beneath the coatings caused by corrosion induced by the wicking of water trapped in the void.

As a result of the inspections, applying coal tar epoxy only will be used to repair 408 protective coatings of the anchor assemblies of the 1656 anchors of the typical spans. Nine other damaged protective coatings were found on the anchor assemblies in the 3-span main channel unit.

3.6 Corrosion Of Prestressing Steel

As a result of the deficiencies in the post-tensioning system of the Mid-Bay Bridge mentioned above, there has been considerable corrosion of the prestressing steel. The following list is a compilation of the features, tendencies, or practices that most likely affected the accelerated corrosion of the tendons.

- The majority of the corrosion occurs at the expansion joint segment anchorages in the tendons of the expansion joint spans. The tendon geometry described earlier led to larger voids and more strands exposed to the moisture in the anchorages.

- The most serious corrosion occurs south of the main span. Project correspondence indicates the approval of the use of an anti-bleed grout mixture on 10/19/92 for future grouting use. Span 69 was stressed the day this letter was issued.

- Water inside the anchors that participated in corrosion most likely came from excessive bleed water and recharging during construction. However, general atmospheric attack and recharge cannot be ruled out. The dates of any pour-backs of grout caps and applications of anchor head protective coatings have not been completely evaluated. Also, expansion joint assemblies were not placed immediately. The concrete pour that secures the expansion joint also provides protection to the expansion joint span anchorages from rain and deck runoff. It does appear, however, the moisture that participated in corrosion was introduced during construction, as protective coatings were found intact at anchors where strand corrosion was found.

- Single-end grouting from the high point most likely entrapped air (cavitation) and subsequently the grout subsided from the anchorages. Grouting rates that may have been too high and could have resulted in turbulent flow may have aggravated the amount of entrapped air and bleed water.

- The protection offered by the polyethylene ducts was compromised by placing small holes in the ducts while inspecting the ducts during construction.

- The protection offered by the polyethylene ducts was compromised by the extensive cracking in the ducts since the completion of construction.

- The high permeability of the grout offers less than expected protection to the prestressing strands. This is even more pronounced when the polyethylene duct is damaged.

- The time interval between removal of post-tensioning steel caps and application of protective coatings may have allowed the recharge of moisture.

- Although the corrosion found in the vicinity of the anchorage assembly was believed to be caused primarily by the presence of grout voids and grout bleed water, this corrosion activity may have been aggravated by galvanic corrosion between two or more dissimilar metals that make up the post-tensioning system. For example, there are at least six different metals in the immediate vicinity of the anchorage assembly (strands, chucks, wedge plate, trumpet, duct pipe, zinc) Except for the zinc, these metals would appear very close on the electromotive series (under standard conditions) and would not be expected to have significant potential differences. Therefore these metals would not be expected to corrode when coupled and surrounded by cured, cement-based grout of reasonable quality. The zinc layer would be expected to be galvanically active during the period of time beginning with the introduction of grout and continue briefly until the grout has cured and developed high electrical resistance. No significant corrosion of the system would be expected for many decades unless the system was to be breeched such that water and oxygen and/or contaminants were allowed to enter the system.

  In instances where the trumpets contain voids and water, corrosion of one or more metals is almost certain to take place. Where the void is sufficiently extensive to involve the galvanized pipe, it would be expected that, at least initially, all of the other metal components in contact with the electrolyte (water and wet grout) would benefit by some degree of cathodic protection because of the highly anodic potential of the zinc and its propensity for rapid dissolution in high pH media such as that which would initially be found in grout bleed-water. The efficiency of the zinc in providing effective cathodic protection to the other metallic components is highly dependent on numerous factors such as solution chemistry and resistivity, oxygen availability and polarization characteristics of both the zinc and the other metals in electrolytic contact with one

another. Likewise, in the absence of the zinc providing a protective function, the other metal components would corrode dependent upon the very same factors.
The actual potential of the individual metals would dictate whether one or more metals would corrode preferentially to another. In this instance, the solution chemistry and oxygen availability would play a significant role in the development of metal potentials and resulting galvanic corrosion rate. Therefore the possibility of galvanic activity between the various metals in the anchorage assembly cannot be ruled out. This is particularly so since it has been clearly shown that prestressed strands are particularly susceptible to corrosion when exposed to grout bleed water. For example, reliable studies (Ref. 1 and 2) have shown the propensity for extremely high corrosion rates for prestressed strands when exposed to grout bleed water. In fact, Reference 2 demonstrated total tendon failure due to corrosion from grout bleed water in just a matter of weeks. Reference 1 demonstrates a particularly high propensity to bleed water development and subsequent strand corrosion when Sika's Interplast N admixture (as used at the Mid-Bay bridge) is used in ordinary grout.

Studies of the actual mechanisms of corrosion are currently being investigated using laboratory mock-ups containing the same components and materials as used at Mid-Bay Bridge. Results of these studies will be forthcoming.

References:

1. *"Performance of Grouts for Post-Tensioned Bridge Structures",* Publication No. FHWA-096, Federal Highway Administration, Washington, D.C., December, 1993*RD-92-095.*

2. *"Implications of Test Results from Full-Scale Fatigue Tests of Stay Cables Composed of Seven- Wire Prestressing Strand",* Habib Tabatabai, A. T. Ciolko and T. J. Dickson, Reprinted from Conference Proceedings 7 of the Fourth International Bridge Conference, Volume 1, Transportation Research Board, National Research Council, Washington, D. C.

The primary reason corrosion has occurred in the post-tensioning tendons of the Mid-Bay Bridge is that water has resided in the tendons, most likely since the time of construction, in enough volume as to not be readily absorbed in the grout as it cured. This, combined with the presence of oxygen, both entrapped and/or diffused into the system over time through holes, cracks or leaks, allowed corrosion to progress. The opportunity for corrosion is enhanced by the configuration of the individual 7-wire strands. Specifically, the interstitial areas give opportunity for numerous locations for a crevice corrosion effect that is further enhanced by strand-to-strand contact within the tendon bundle. Visual observations of partially or completely failed tendons indicated that corrosion occurred over time, as there were numerous wire breaks that had continued corrosion on the broken surfaces and rounding of broken wire edges.

Chapter 4 – Post-Tensioning System Rehabilitation

4.1 Introduction

This chapter focuses on the remedial actions that will or have been undertaken to rehabilitate the post-tensioning system of the Mid-Bay Bridge. The rehabilitation efforts are grouped into the following general categories:

- Replacement of Post-Tensioning Tendons
- Repair of Tendon Anchorages
- Duct Wrapping

Eleven post-tensioning tendons have been replaced to date. Repairs to tendon anchorages are under way. Some duct wrapping has begun, with the majority of work remaining. Selected anchorages have been injected with the remaining anchorages with voids scheduled for repair in the next weeks.

4.2 Replacement of Post-Tensioning Tendons

Eleven post-tensioning tendons were identified as needing replacement during the inspection of the Mid-Bay Bridge. A replacement criterion was established based on early inspection results and engineering judgment. Subsequent structural analyses have verified the concerns of the load carrying capacity of the bridge with reduced post-tensioning levels. The following are the components of the tendon replacement criteria:

- The corrosion appears to have caused a 25% loss in strength of the entire tendon. The 25% loss may be a combination of pitting corrosion with observed broken wires or strands.
- No two post-tensioning tendons on the same side of the box girder, in the same span could have significant section loss.
- The bore scope inspections were reviewed with regard to extent of corrosion, number of strands visible, depth of the void in the grout, depth of penetration of the bore scope.
- Each candidate for replacement received a callback bore scope inspection.
- Two Certified Bridge Inspectors and two Professional Engineers reviewed the results of the callback inspection.

The remainder of this section documents the facts about tendons that were replaced and details of the replacement procedure. The original construction details are being reviewed for documentation that may lead to a tie between exposure opportunities for contamination and recharge of the voids at the expansion joints. This is primarily from the observation that 10 of the 11 tendons that were replaced were in expansion joint spans.

4.2.1 Span 28 - Tendon 6

This tendon was one of the two failed post-tensioning tendons that were originally discovered during the annual inspection on August 28, 2000. A description of this tendon is found in Section 1 of Chapter 3. The tendon had already been replaced when the bore scope inspections were started.

Span Type: Expansion Joint Span
Date Stressed: 7/25/92
Date Grouted: 7/28/92
Date Protected: TBD
Date Expansion Joint Placed: 10/21/92

4.2.2 Span 57 - Tendon 1

Like Tendon 28-6, this tendon was one of the post-tensioning tendons that had failed and was discovered during the annual inspection. A description of this tendon is found in Section 1 of Chapter 3. The tendon had already been replaced when the bore scope inspections were started.

Span Type: Expansion Joint Span
Date Stressed: 9/18/92
Date Grouted: 9/25/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

4.2.3 Span 9 Tendon 1

Span Type: Expansion Joint Span
Date Stressed: 6/16/92
Date Grouted: 6/24/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:

Photograph of Tendon 1 of Span 9 to be inserted

Photograph of Tendon 1 of Span 9 to be inserted

Bore Scope Field Notes:

North Anchor – 3 to 4 strands visible, black and gray heavy corrosion on bottom of strands, broken grout, red and black (active) corrosion.
South Anchor - Information to be provided

Photographs of removed tendon:

4.2.4 Span 57 Tendon 2

Span Type: Expansion Joint Span
Date Stressed: 9/18/92
Date Grouted: 9/25/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:

Bore Scope Field Notes:

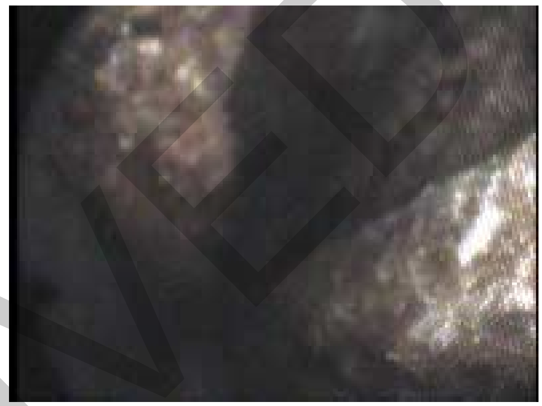
North Anchor – 6 strands visible with deep pits, 18" to 28" of penetration, bright copper, orange corrosion on tendons, active corrosion on side of trumpet
South Anchor – 2 ½" void then solid grout, no video

Photographs of removed tendon:

4.2.5 Span 58 Tendon 5

Span Type: Expansion Joint Span
Date Stressed: 9/19/92
Date Grouted: 9/25/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:



Bore Scope Field Notes:

North Anchor – no corrosion, white grout
South Anchor – no grout present, 8 to 10 strands visible, severe corrosion, active corrosion cells, wires on strands could not be distinguished due to corrosion for approximately 4” to 6”

Photographs of removed tendon:

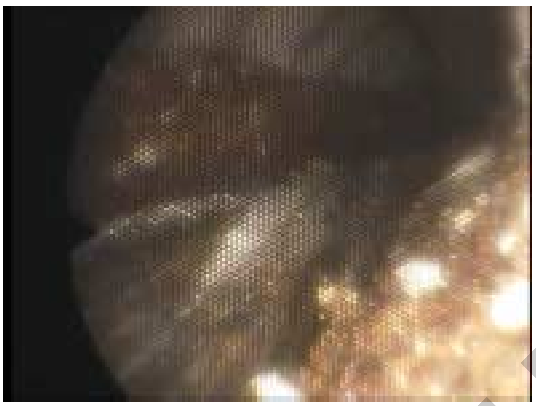
Photograph to be inserted

Photograph to be inserted

4.2.6 Span 69 Tendon 3

Span Type: Expansion Joint Span
Date Stressed: 10/19/92
Date Grouted: 10/21/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:



Bore Scope Field Notes:

North Anchor – 3' void, 5 to 7 strands visible, appears to be necking
South Anchor – small void, black corrosion on trumpet, 8" void

Photographs of removed tendon:

Photograph to be inserted

Photograph to be inserted

4.2.7 Span 63 Tendon 6

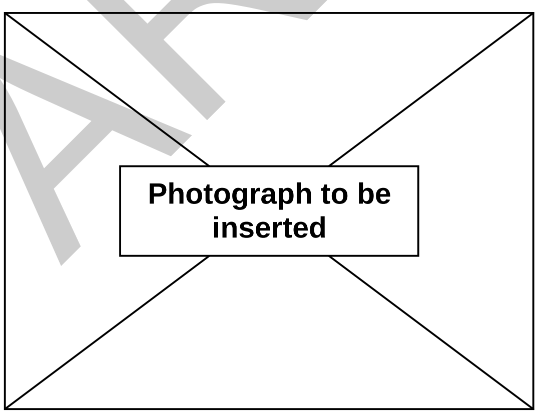
Span Type: Expansion Joint Span
Date Stressed: 9/25/92
Date Grouted: 10/8/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

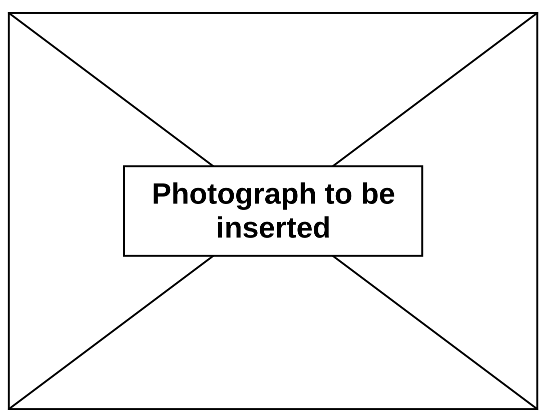
Bore Scope Photographs:

Bore Scope Field Notes:

North Anchor – 5' void, 5 strands visible, trumpet has advanced corrosion with pitting, several strands with advanced corrosion and what appears to be pitting.
South Anchor – 3 strands visible with light orange spotty corrosion, moderate corrosion on trumpet, white grout, and 2' penetration.

Photographs of removed tendon:





4.2.8 Span 58 Tendon 6

Span Type: Expansion Joint Span
Date Stressed: 9/19/92
Date Grouted: 9/25/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:

Bore Scope Field Notes:

North Anchor – no corrosion, white grout
South Anchor – 3'-6" void, 8 to 9 strands visible, severe corrosion, active corrosion cells, wires on strands could not be distinguished due to corrosion for approximately 12"

Photographs of removed tendon:

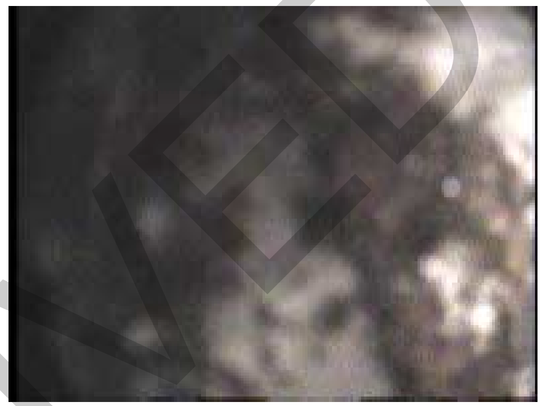
Photograph to be inserted

Photograph to be inserted

4.2.9 Span 64 - Tendon 1

Span Type: Expansion Joint Span
Date Stressed: 9/30/92
Date Grouted: 10/8/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:



Bore Scope Field Notes:

North Anchor –	moderate corrosion on trumpet, no strands visible, white grout, 1'-6" void
South Anchor –	3' void plus, 5 strands visible, wires on strands cannot be distinguished, severe corrosion present, active corrosion cells. Face of diaphragm at pier 64 has three diagonal cracks adjacent to all of the ducts, effervescence present at the top of deck underside adjacent to duct 64-1.

Photographs of removed tendon:

Photograph to be inserted

Photograph to be inserted

4.2.10 Span 69 Tendon 2

Span Type: Expansion Joint Span
Date Stressed: 10/19/92
Date Grouted: 10/21/92
Date Protected: TBD
Date Expansion Joint Placed: TBD

Bore Scope Photographs:

Bore Scope Field Notes:

North Anchor – 18” void, 5 strands visible, extremely heavy corrosion, active corrosion cells on strands
South Anchor – good white grout, 6” void

Photographs of removed tendon:

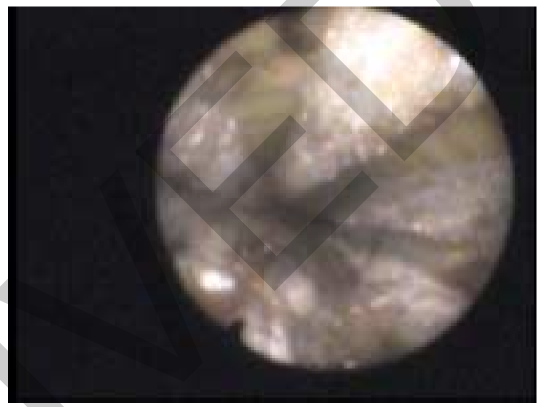
Photograph to be inserted

Photograph to be inserted

4.2.11 Span 48 - Tendon 5

Span Type: Interior Span
Date Stressed: 9/4/92
Date Grouted: 9/10/92
Date Protected: TBD
Date Expansion Joint Placed: n/a

Bore Scope Photographs:



Bore Scope Field Notes:

North Anchor – 12” void, white grout, light red corrosion on trumpet
South Anchor – 5 to 6 visible strands, 1 strand has a broken wire, moderate to heavy corrosion on all strands with pitting and blistering, moderate to heavy corrosion on trumpet, white grout

Photographs of removed tendon:

Photograph to be inserted

Photograph to be inserted

4.2.12 Removal and Replacement of Span-By-Span, External Post-Tensioning Tendons

The following are the steps taken by the Contractor to remove an external tendon from the Mid-Bay Bridge.

1. Remove the PE pipe from the entire length of the tendon.
2. Locally remove grout and install 4-inch diameter heavy-duty U -bolt clamps every 4 ft. on the tendon to control the possible strand 'whip-lash' as each strand is cut.
3. Remove as much grout as practical throughout the entire length of the tendon.
4. Remove as much grout as possible from the steel ducts at the deviation diaphragms using a high-pressure hydro-blaster (to decrease bond at the deviation diaphragms).
5. Strand cutting will be performed with an electric powered cut-off saw using metal abrasive blades. Torch cutting will not be allowed.
6. Cut one strand of the tendon at the down station side of the down station deviation diaphragm. (Leaving enough strand length so that a mono-strand jack can be used to grip the strands and remove them later)
7. Cut one strand at location up station side of the down station deviation diaphragm.
8. Repeat Steps 6 and 7 at the up-station deviation diaphragm.
9. Repeat Steps 6, 7, and 8 never allowing more than one strand cut out of balance at any deviation diaphragm.
10. Check that cut strands are shortening by the appropriate amount to relieve their stress. If not, loosen U-bolt clamps to allow cut strands to slide along their length.
11. When all strands are cut, use the remaining tails to pull out the strand at the deviation saddles.
12. Use hydro-blaster to remove grout in the pier segment diaphragms.
13. Remove anchor plate using air assisted arc cutter to control amount of heat required. Acetylene torches generally pop more around cementitious grout and destroy tips on the torch. Ventilation was critical for worker safety.
14. Use tails of strands to remove the tendon from the pier segment diaphragms.
15. Place new polyethylene duct.
16. Push strands in place, starting from the bottom of the duct. Use a locating plate to guide the strands in the duct to prevent twisting of the tendon bundle in the duct.
17. Pull initial load on all strands using monostrand jack, starting at the top of the tendon.
18. Apply final stressing of strands working from the strands in the top of the duct to the strands at the bottom. (Use of a multi-strand jack is permitted for Steps 17 and 18 if access and clearances are sufficient).
20. Cut tails and cap vents and ports in the tendon duct within 4 hours after stressing*.
21. Grout tendon within 7 days*.
22. Leave grout cap on as protection for a minimum of 72 hours after grouting*.
23. Remove grout cap and inspect for voids*.
24. Cast pour-back within a minimum of 54 hours following inspection for voids*.
25. Apply mastic protective covering within 4 hours of removing forms of the pour-back*.

* In accordance with the new FDOT post-tensioning specification.

The total cost to replace the 11 tendons in the Mid-Bay Bridge was $999,680.

Figure 4.1 – Details of the Removal of External Tendons (Clockwise from upper left: clamping strands, cutting cable, hydro-blasting at pier segment diaphragm, and hydro-blasting operator)

4.3 Repair of Tendon Anchorages

All grout injection ports are sealed at this time to limit the entrance of additional moisture into the voided anchors. The following is a description of the approved methods and materials developed by the FDOT Central Structures Office for the repair of the post-tensioning system of the Mid-Bay Bridge.

Various methods for cleaning the voids prior to re-injection were investigated. Consideration was given to cleaning by flushing the voids with either water alone or water with a concentration of lime. Protecting strands by placing corrosion inhibitors was also studied. This would require that some water be introduced during application or that water be used to clean the strands prior to grouting. The decision was made, based on the apparent condition of the existing grout and possible wicking action of the strands, that adding any water to the voids could do more harm than good. As a result, the voids will only be prepared by removing debris using compressed air.

After a detailed inspection, the following list of needed repairs was established:

A. Replace all pour-backs located at expansion joint piers - 89 required
B. Grout anchorage voids with strands visible - 274 required

C. Grout anchorage voids without strand visible - 316 required
D. Replace pour-back at interior piers - 307 required
E. Coat undamaged pour-backs with coal tar epoxy - 408 required

4.3.1 Replacement of Pour-Backs at Expansion Joint Piers

Remove all coal tar epoxy from expansion joint pier segments by mechanical cleaning. Remove grout cap material and any scaling corrosion products to bare metal by mechanical cleaning. Immediately after cleaning, form the new pour-back and cast full using a flow and fill epoxy compound. Coat the pour back and adjoining concrete surface with coal tar epoxy.

4.3.2 Vacuum Grouting of Anchor Voids

Clean the void by blowing compressed air through the grout port using a wand. Continue blowing air into the void until debris and dust stop exiting the grout port. After cleaning, prepare void for vacuum injection by sealing all air leaks. Vacuum inject grout from the void (See Chapter 2, Section 2.7 for injection procedures).

4.3.3 Replacement of Pour-Back at Interior Piers

Remove grout cap material and any scaling corrosion products to bare metal by mechanical cleaning. Install non-metallic grout cap that mounts to the exposed face of the multi-plane anchor. This grout cap covers the strands and wedge plate allowing for complete encapsulation of the anchor hardware. Using a tube completely fill the grout cap with cementitious grout. Apply two coats of coal tar epoxy to the grout cap and the adjoining concrete surface.

4.3.4 Sealing of Existing Pour-Backs

Sound pour-back with hammer for solid or hollow response. Visually inspect anchorage for signs of corrosion. If a hollow response or corrosion is observed, remove the pour back and replace in accordance with the procedures of Section 4.3.3. If a solid response and no corrosion are observed, apply two coats of coal tar epoxy to the pour-back and the adjoining concrete surface.

4.3.5 Approved Materials

All materials shall be used in strict accordance with the manufacturers instructions.

Cement Grout:	Master Flow 816 Cable Grout
Coat Tar Epoxy:	Bitumastic 300M
Grout Cap:	DSI Grout Cap 68197210 and "0" ring gasket. Use this grout cap at all locations except at expansion joints.
Epoxy Grout:	Ceilcote 648 CP Plus

4.4 Duct Wrapping

The loss of post-tensioning tendons to corrosion elevates the cracking of the duct from a maintenance issue to one of fundamental importance. The polyethylene duct serves as the outer defense for the corrosion protection of the prestressing strands. Several locations of localized corrosion in the Mid-Bay Bridge were found where the duct was punctured during a construction inspection, in spite of being filled with grout. One of the failed tendons, Tendon 28-6 failed in the free length of tendon where only the grout and polyethylene duct are providing protection.

As a result of the extensive cracking of the ducts, a significant program of wrapping the ducts of the bridge is planned. The total length of duct to be wrapped is 115,000lf. To date, approximately 10,000 linear feet have been wrapped, leaving 105,000 linear feet to be wrapped. The cost of duct wrapping is between $25 and $40 per linear foot of duct, based on the quantity being installed.

Figure 4.2 shows a wrapped portion of a tendon at the Mid-Bay Bridge. The final version of this report will include details and material to be used for the wrapping of the polyethylene duct.

Figure 4.2 – Heat Activated Adhesive Duct Wrapping for External Post-tensioning Tendons

Chapter 5 – Structural Analyses

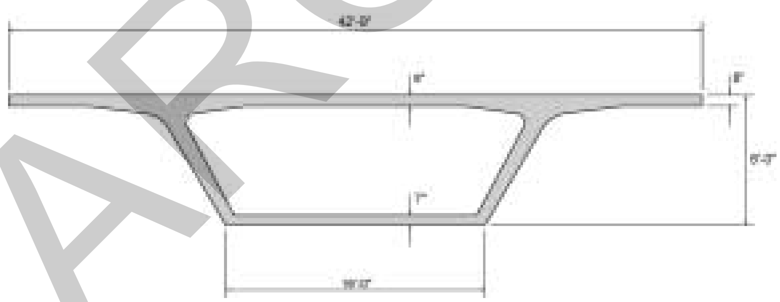
5.1 Introduction

Structural analyses were performed for a typical 6-span unit of the Mid-Bay Bridge. These analyses were undertaken to better understand the behavior of the bridge, as post-tensioning tendons are lost as a result of corrosion. This work was accomplished using the two-dimensional, time-dependent computer program Bridge Designer II (BDII). The BDII program models the bridge components and construction staging consistent with the actual construction of the Mid-Bay Bridge. BDII also evaluates traffic effects on the bridge that represent the design live loadings and legal rating vehicles used by the Florida Department of Transportation (FDOT). The results presented in this Chapter are Rating Factors for the design and legal trucks, for various configurations of prestressing in a typical 6-span unit.

5.2 Analysis Parameters

The typical 6-span unit is made of four interior typical spans and two expansion joint spans at either end of the unit. The span length of the typical spans is 136' and the span length of the expansion joint spans (to the centerline of the expansion joint bearings) is 133'-6". The distribution of the segments in the typical and expansion joint spans is shown in Chapter 1, Figure 1.4.

The cross section used in the modeling of the typical 6-span unit is the single-cell box girder shown in Figure 1.2 of Chapter 1. This cross section is presented again in Figure 5.1 along with the cross section properties used in the structural analyses.



Area = 58.13 ft^2
c_{top} = 2.4734 ft
c_{bottom} = 5.5266 ft
Inertia = 487.84 ft^4
Efficiency = 0.6139

Figure 5.1 – Mid-Bay Bridge Cross-Section Properties

The analysis made by the BDII program is a two-dimensional, time-dependent frame analysis of a bridge model. Nodes, which have three degrees of freedom for displacement (vertical, horizontal and in-plane rotation), are defined at specific locations to model the bridge geometry. The nodes are related to each other in the model by the definition of frame elements that have desired member characteristics. Nodes for the typical 6-span model of the Mid-Bay Bridge are located at joints between the precast elements, closure joints, and at support locations. The frame element characteristics are those of the typical cross section presented in Figure 5.1.

Post-tensioning tendons are defined as per the details presented in the design drawings, with consideration given to the location of strands within the ducts.

An analysis using the BDII program can include the time-dependent characteristics of the concrete and prestressing steel used to build concrete segmental bridges. Using an iterative approach, the effects of concrete creep, concrete shrinkage and prestressing steel relaxation on the state of stress in the bridge are evaluated. The variations of these characteristics used for these analyses were those presented in the FIP-CEB Model Code used in Europe. This is the same approach as was taken during the original design.

Each time-dependent analysis establishes a timeframe relative to the casting and erection of the portion of bridge being analyzed. For this study, the following timeframe was established based on project documentation for the average ages of all of the segments at the time of erection.

Casting Date of All Segments of the unit – Day 0
Erect Span 1 – Day 50
Erect Span 2 – Day 52
Erect Span 3 – Day 54
Erect Span 4 – Day 56
Erect Span 5 – Day 58
Erect Span 6 – Day 60
Place Barrier Railing – Day 74

External loadings for the analyses were taken from the General Notes of the design plans. Barrier Railing loads and weights of internal diaphragms were computed from the plan concrete dimensions. The thermal gradient used in the original design was an 18°F linear gradient (top slab warmer than bottom slab). Though current code requirements are slightly different, these analyses used the same 18°F linear gradient for comparative purposes.

5.3 Code Changes and Load Rating

Developing the load ratings for a concrete segmental bridge is an involved process that begins with the time-dependent analysis and concludes with the verification of each section of the bridge with regard to the effects of the different rating vehicles. This effort can be further complicated by the fact that design code requirements governing segmental bridges have changed since first introduced.

The Mid-Bay Bridge is one of several bridges in Florida whose ratings today are affected by updates to governing codes. The "*Guide Specification for Design and Construction of Segmental Concrete Bridges"* (Guide Specifications) was developed in 1988 as a NCHRP project and subsequently adopted as a guide specification by the Highway Subcommittee on Bridges and Structures of AASHTO in 1989. The Mid-Bay Bridge was under design in 1989 and the first span of the bridge was stressed on May 16, 1992. In 1999 AASHTO approved the 2nd Edition to the guide specifications, incorporating interim revisions to the 1st Edition and input from a committee that consisted of state and federal highway officials, consultants, contractors, suppliers, and academicians. FDOT practice is to rate bridges in accordance with current applicable codes and Volume 3 of FDOT publication "*Bridge Load Rating, Permitting and Posting Manual."*

Significant changes in the Guide Specifications with regard to the Mid-Bay Bridge are:

Service Load Flexure: The 1st Edition permitted reduction of variable load effects (interpreted as the live loads and gradients in the original design) by the overstress factors in the AASHTO Code and allowed zero tension for bridges with dry (non-epoxied) joints.

The 2nd Edition does not permit reduction of variable load effects and requires a 100 psi residual compression in bridges with Type B (non-epoxied) joints.

Ultimate Flexural Strength: The 1st Edition included gradient effects in ultimate load combinations and allowed an increase of 15 ksi in the stress in prestressing steel at ultimate for unbonded tendons.

The 2nd Edition assigns a load factor of zero to gradient effects in ultimate load combinations and allows an increase in prestressing steel stress as a function of free length of tendon for deviated external tendon. The AASHTO Code supplies an upset limit to this stress increase equal to the yield stress of the prestressing (0.9 of the ultimate strength for low-relaxation steel).

Shear: The 1st Edition used a capacity reduction factor for shear of 0.9.

The 2nd Edition reduced the capacity reduction factor to 0.85.

5.4 Load Rating and Parametric Study Results

Load ratings and parametric studies were performed for a typical 6-span unit of the Mid-Bay Bridge. The load ratings were conducted in accordance with Volume 3 of the FDOT publication "*Bridge Load Rating, Permitting and Posting Manual.*" The typical 6-span unit with original post-tensioning was rated with and without the effects of the future wearing surface that is called for in the project plans. Other parameters of the load ratings were:

- Inventory ratings were developed for the HS-20 Truck only.
- Operating ratings were developed for the HS-20 Truck and the seven legal trucks defined in the FDOT load rating publication.
- Flexural load ratings at inventory and operating level were developed considering zero tension at the joints between precast segments.
- Shear load ratings were performed at load factor level considering the appropriate load magnification for inventory and operating ratings.
- A capacity reduction factor (ø) equal to 0.85 was used in the shear load ratings.

The results of the load ratings for shear and flexure, with and without future wearing surface are given in Table 5.1 and Table 5.2, respectively. These results are expressed as Rating Factors that give a relative measure of the number of loadings that the bridge can support. A Rating Factor equal to 1.0 would indicate that the bridge could support the vehicle in question placed in the three design lanes of the Mid-Bay Bridge, with the appropriate 0.9 lane reduction factor. The bridge ratings are also given in terms of the number of individual design lanes that the typical unit can support. These values are given in parentheses in Tables 5.1 and 5.2. The number of single design lanes (the values in parentheses) is found by multiplying the Rating Factor by 2.7 (3 lanes x 0.9 reduction = 2.7).

		Ratings without Future Wearing Surface					
		Flexure		Shear		Governing	
Inventory Ratings		1.27	(3.43)	1.32	(3.56)	1.27	(3.43)
Operating Ratings	HS20 Truck	1.27	(3.43)	2.37	(6.40)	1.27	(3.43)
	SU2 Truck	2.34	(6.32)	4.48	(12.10)	2.34	(6.32)
	SU3 Truck	1.27	(3.43)	2.32	(6.26)	1.27	(3.43)
	SU4 Truck	1.18	(3.19)	2.23	(6.02)	1.18	(3.19)
	C3 Truck	1.78	(4.81)	2.95	(7.97)	1.78	(4.81)
	C4 Truck	1.35	(3.65)	2.46	(6.64)	1.35	(3.65)
	C5 Truck	1.44	(3.89)	2.36	(6.37)	1.44	(3.89)
	ST5 Truck	1.45	(3.92)	2.72	(7.34)	1.45	(3.92)

Table 5.1 – Load Rating for 6-span Unit of the Mid-Bay Bridge (no wearing surface).

		Ratings with Future Wearing Surface					
		Flexure		Shear		Governing	
Inventory Ratings		1.20	(3.24)	1.20	(3.24)	1.20	(3.24)
Operating Ratings	HS20 Truck	1.25	(3.38)	2.16	(5.83)	1.25	(3.38)
	SU2 Truck	2.38	(6.43)	4.08	(11.02)	2.38	(6.43)
	SU3 Truck	1.24	(3.35)	2.11	(5.70)	1.24	(3.35)
	SU4 Truck	1.17	(3.16)	2.03	(5.48)	1.17	(3.16)
	C3 Truck	1.61	(4.35)	2.68	(7.24)	1.61	(4.35)
	C4 Truck	1.25	(3.38)	2.24	(6.05)	1.25	(3.38)
	C5 Truck	1.26	(3.40)	2.15	(5.81)	1.26	(3.40)
	ST5 Truck	1.24	(3.35)	2.47	(6.67)	1.24	(3.35)

Table 5.2 – Load Rating for 6-span Unit of the Mid-Bay Bridge (with wearing surface).

The Rating Factors presented in Tables 5.1 and 5.2 indicate that the bridge, in pristine condition, would be able to carry the design live load (HS-20 truck) as well as the weight of more than one of each of the seven legal trucks in the appropriate number of design lanes.

Parametric studies were made to model the effects of the loss of post-tensioning tendons due to corrosion. Unit 10, which contains Spans 52 through 57, was considered. Tendon 57-1 had failed completely due to corrosion and Tendon 57-2 was subsequently replaced after inspection revealed extensive deterioration. Span 57 is represented as Span 6 in the computer models developed. The following combinations of prestressing configurations were considered:

- All spans constructed with all post-tensioning in place.
- All spans constructed, all tendons stressed, then Tendon 1 in Span 6 removed.

- All spans constructed, all tendons stressed, then Tendons 1 and 2 in Span 6 removed.
- All spans constructed, all tendons stressed and Tendons 1 and 6 in Span 6 removed. This case was considered for shear only, in order to investigate the loss of those tendons most beneficial to resisting shear at the expansion joint end of the expansion joint spans.

Table 5.3 shows the impact of the reduction of post-tensioning on flexural capacity in Span 6, expressed in terms of Rating Factors. As in Tables 5.1 and 5.2, the numbers in parentheses represent the number of individual design lanes that can be supported by the bridge according to the FDOT rating guidelines.

		Flexural Parametric Study - No Wearing Surface					
		Full PT		T1 Removed		T1 & T2 Removed	
Inventory Ratings		1.27	(3.43)	0.71	(1.92)	-0.03	-(0.08)
Operating Ratings	HS20 Truck	1.27	(3.43)	0.71	(1.92)	-0.03	-(0.08)
	SU2 Truck	2.34	(6.32)	1.42	(3.83)	-0.06	-(0.16)
	SU3 Truck	1.27	(3.43)	0.74	(2.00)	-0.03	-(0.08)
	SU4 Truck	1.18	(3.19)	0.69	(1.86)	-0.03	-(0.08)
	C3 Truck	1.78	(4.81)	0.96	(2.59)	-0.04	-(0.11)
	C4 Truck	1.35	(3.65)	0.74	(2.00)	-0.03	-(0.08)
	C5 Truck	1.44	(3.89)	0.75	(2.03)	-0.03	-(0.08)
	ST5 Truck	1.45	(3.92)	0.74	(2.00)	-0.03	-(0.08)

Table 5.3 – Effect of Post-Tensioning Loss on Rating Factors (results with gradient).

The results of the parametric study shown in Table 5.3 indicates that Span 6 can support only 71% of the design lanes with no tension at the joints when Tendon 1 is removed. This represents 1.92 individual design lanes of the AASHTO HS20 Truck (0.71 x 3 x 0.9). Or in terms of two lanes, the Mid-Bay Bridge can support two lanes of HS19 trucks when one tendon is removed from the expansion joint spans.

Table 5.3 shows negative values for the when both Tendon 1 and Tendon 2 are removed from Span 6. These negative results indicate that there is no live load capacity in the bridge with respect to joint openings with two tendons removed in an expansion joint span. The results indicate that the joints would open in this span under the influence of thermal gradient only.

Table 5.4 is similar to Table 5.3 in that it presents the effects of the loss of post-tensioning on the flexural capacity of Span 6 in the typical 6-span unit of the Mid-Bay Bridge. The values in this table do not include the effects of thermal gradient.

		Flexural Parametric Study - No Wearing Surface					
		Full PT		T1 Removed		T1 & T2 Removed	
Inventory Ratings		1.56	(4.21)	0.87	(2.35)	0.13	(0.35)
Operating Ratings	HS20 Truck	1.56	(4.21)	0.87	(2.35)	0.13	(0.35)
	SU2 Truck	3.10	(8.37)	1.73	(4.67)	0.26	(0.70)
	SU3 Truck	1.61	(4.35)	0.90	(2.43)	0.14	(0.38)
	SU4 Truck	1.52	(4.10)	0.85	(2.30)	0.13	(0.35)
	C3 Truck	2.09	(5.64)	1.17	(3.16)	0.17	(0.46)
	C4 Truck	1.62	(4.37)	0.91	(2.46)	0.14	(0.38)
	C5 Truck	1.63	(4.40)	0.91	(2.46)	0.14	(0.38)
	ST5 Truck	1.61	(4.35)	0.90	(2.43)	0.13	(0.35)

Table 5.4 – Effect of Post-Tensioning Loss on Rating Factors (results without gradient).

The effect of the loss of post-tensioning tendons in Span 6 on shear capacity is presented in Table 5.5. Although capacity reduces with the loss of post-tensioning, the impact on the ability of the Mid-Bay Bridge to carry shear is not as pronounced as for resistance to flexure. This is primarily the result of good shear characteristics of the concrete box girder and the ability to rate shear at ultimate load levels. It is important to note that actual behavior of the end of the expansion joint span will be somewhat different from these results as the 3-dimensional effects of torsion, out of plane bending, distribution of prestressing forces, and shear lag are not included.

		Shear Parametric Study - No Wearing Surface							
		Full PT		T1 Removed		T1 & T2 Removed		T1 & T6 Removed	
Inventory Ratings		1.32	(3.56)	1.17	(3.16)	1.00	(2.70)	0.92	(2.48)
Operating Ratings	HS20 Truck	2.37	(6.40)	2.01	(5.43)	1.69	(4.56)	1.52	(4.10)
	SU2 Truck	4.48	(12.10)	3.81	(10.29)	3.19	(8.61)	2.87	(7.75)
	SU3 Truck	2.32	(6.26)	1.97	(5.32)	1.65	(4.46)	1.49	(4.02)
	SU4 Truck	2.23	(6.02)	1.89	(5.10)	1.59	(4.29)	1.43	(3.86)
	C3 Truck	2.95	(7.97)	2.50	(6.75)	2.09	(5.64)	1.89	(5.10)
	C4 Truck	2.46	(6.64)	2.09	(5.64)	1.75	(4.73)	1.58	(4.27)
	C5 Truck	2.36	(6.37)	2.00	(5.40)	1.68	(4.54)	1.51	(4.08)
	ST5 Truck	2.72	(7.34)	2.30	(6.21)	1.93	(5.21)	1.74	(4.70)

Table 5.5 – Effect of Post-Tensioning Loss on Rating Factors

5.5 Structural Analyses and FDOT Actions

Immediately following the discovery of the failed post-tensioning tendons in Span 28 and 57, the Florida Department of Transportation took important steps to assure safe operation of the Mid-

Bay Bridge. Two important actions taken were two closures of the bridge to all traffic and two other closures of the bridge to truck traffic (see Section 1.3).

Initial calculations, developed according to the 1st Edition of the Segmental Guide Specifications (see Section 5.3), were prepared to justify two lanes of traffic on the bridge with one post-tensioning tendon removed in a span. Though not in agreement with the use of the 1st Edition for the evaluation of load carrying capacity, the FDOT did realize these calculations indicated there was no live load capacity, with respect to joint openings, when two tendons were removed from a span.

The immediate response of closing the bridge on August 28th and 29th to all traffic allowed the FDOT time to perform vibration testing on the remaining five tendons in each of Spans 28 and 57, without risking the failure of a second tendon with traffic on the bridge. Base on the results of this vibration testing, the bridge was re-opened to two-axle vehicles. From August 29th to September 11th the FDOT developed procedures to remove a partially stressed post-tensioning tendon. On September 11th it was decided that the vibration testing would not be solely relied upon to establish confidence in the other five tendons in Span 28. As a result, selected bore scope testing was performed in this span. These inspections confirmed that two lanes of traffic with 2-axle vehicles only could use the bridge during replacement of Tendon 28-6.

From September 11th to September 26th several activities were underway at the bridge site. Construction crews were replacing Tendons 28-6 and 57-1, grout cap damage was being inventoried, and bore scope inspections of Spans 1 through Span 9 and other random locations were performed. The severity of the corrosion found in the bore scope inspections lead the FDOT to recommend to the Mid-Bay Bridge Authority to close the bridge completely so thorough inspections could be performed. The Mid-Bay Bridge Authority closed the bridge to all traffic from September 27th to October 11th.

Inspection crews were assembled from around the state, and work began to bore scope inspect every anchor along with vibration testing of every tendon while the bridge was closed from September 27th to October 11th. Construction crews continued tendon removal and installation activities during this bridge closure as tendons were identified for replacement. On October 11th enough information had been gathered and enough repairs had taken place to again have confidence in the bridge's ability to carrying two lanes of two-axle vehicles.

The load ratings and parametric studies presented in Section 5.4 were performed subsequent to the FDOT response to the tendon failures, and were not available to assist the FDOT in determining the capacity of the bridge during tendon replacement. These studies do, however, confirm FDOT actions to close the bridge when one tendon in a span is failed and the condition of the other tendons in that span is suspect. These actions were further affirmed when three spans, Spans 57, 58, and 69, were each found to have second tendons that required replacement.

The analytical studies presented in this report also support the FDOT position of allowing only two axle vehicles on the bridge during later tendon replacement. This is seen in the results presented in Table 5.3 where only the SU2 vehicle rates higher than 1.0 when one tendon is removed.

The analytical studies of the typical 6-span unit of the Mid-Bay Bridge is part of a larger effort to rate the longitudinal flexural and shear behavior of all continuous units of the bridge. Subsequent studies of a 4-span unit, 5-span unit, and the 3-span main unit will complete this effort.