Design Features and Prestressing Aspects of Long Key Bridge

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Long Key Bridge, a spectacular example of the economies to be gained by using precast prestressed segmental construction, is now complete. The bridge was constructed at a record pace some 8 months ahead of schedule.

Located 90 miles (145 km) south of Miami in the Florida Keys, the Long Key Bridge will serve as an important link to residents of the islands and tourists. The bridge is replacing the rapidly deteriorating current structure which was completed almost 70 years ago; it will also contain a vital waterline that functions as the only fresh water supply to the area.

The Keys are a series of coral islands which have served as a popular resort area for many decades due to the tropical climate and clear waters. All 37 bridges along the single highway serving the Keys are now being replaced, and the Long Key Bridge is one of the major structures.

The bridge consists of 101 spans, each 118 ft (36 m), plus two end spans for an overall length of 12,144 ft (3701 m). These span lengths are not particularly large in comparison to some bridges around the world. However, what really makes the bridge significant is that for the first time in North America several new design ideas and construction techniques have been found very workable and economical on a project of major proportions.

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Describes the principal design features of Long Key Bridge together with the production and erection of precast segments and post-tensioning operations.

The typical span length of 118 ft (36 m) was established to align the new piers with the 59-ft (18 m) arch spans of the existing structure, which will remain in place after completion of the new bridge. Originally, the existing bridge had been constructed to carry rail traffic, but is now used only for vehicular traffic. The old structure will not only serve as an historical monument but will also be opened to the public for fishing.

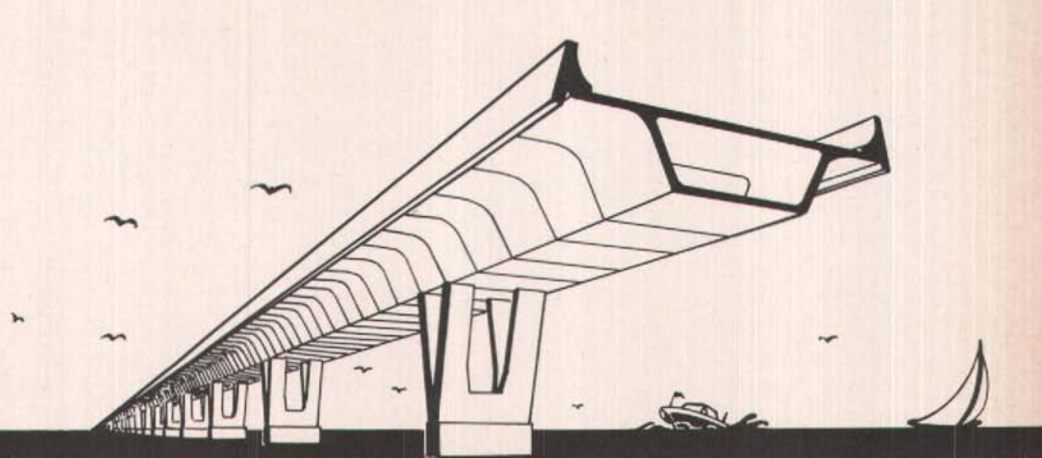
Bidding for construction of the bridge was in June 1978. The competition was on the basis of eight alternates contained in the bidding documents. The alternates included variations in the substructure, erection method, and reinforcement, in addition to the use of precast AASHTO girders in combination with a cast-in-place deck.

The low bidder, Michael Construction Co., was awarded the construction contract in July 1978, for a total price of $15.3 million including approaches. That very favorable price amounted to only $26.63 per sq ft of deck area for the structural items. The superstructure portion was $21.43 per sq ft; the substructure, $5.20 per sq ft. Of eight contractors bidding, seven bid with precast segmental; the single bidder with AASHTO girders was $2.6 million (17 percent) higher than the low bidder.

It then became apparent that segmental box girders could indeed be competitive with other systems in the short and medium span range; subsequent awards on similar bridges have shown this situation to remain valid.

Unique Design Features

The magnitude of the bridge replacement program in the Florida Keys and the potential application of similar cost reduction measures in other areas of North America prompted the use of a



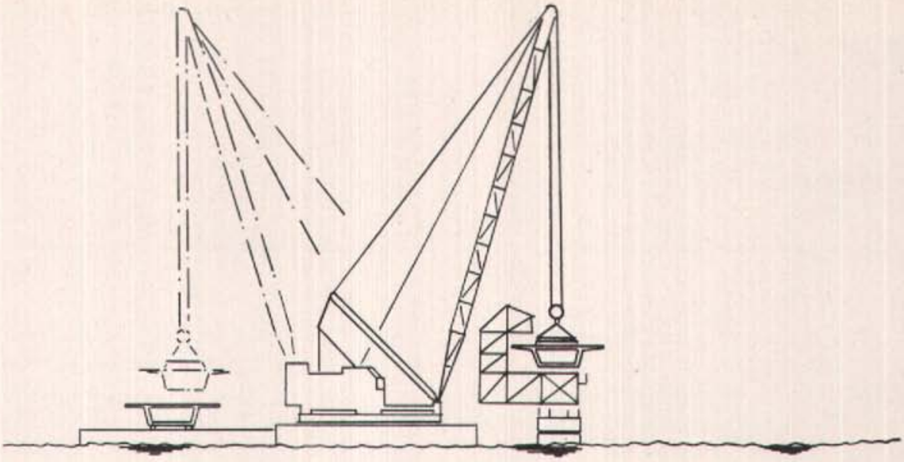


Fig. 1a. Placing precast segments.

number of innovative design features and new construction methods.

These design ideas and construction techniques were developed by Jean Muller in association with Figg and Muller Engineers, Inc. This firm was selected by the Florida Department of Transportation to design Long Key Bridge including several of the major replacement structures in the Florida Keys. Construction supervision was also provided by Figg and Muller.

Long Key Bridge is designed for economy in many different ways. The application of several unique features has resulted in a bridge design which simplifies construction, makes efficient use of materials, and requires practically no maintenance. These features are now described:

Span-by-span erection—The concept of erecting all segments in a span on a temporary support structure allows more efficient use of materials and equipment; the bridge does not have to be designed for loads or conditions other than the final configuration. No intermediate or temporary post-tensioning system is required and no allowance is necessary for construction loads in excess of normal traffic loading.

External tendons—In combination with span-by-span erection, the post-tensioning system is designed with the use of external tendons; i.e., tendons not contained within the concrete, although they are in the void of the box girder section. Protection of the tendons is effected by containment of each tendon within a polyethylene duct.

Dry joints—Segments are designed to be assembled without epoxy in the match cast joints since one main function of epoxy is usually to provide a seal for tendons penetrating the joints; thus, the use of external tendons eliminates the need.

Multiple shear keys—A more uniform transfer of shear stresses across match cast joints is provided by the use of multiple shear keys. Developed several years ago by Jean Muller in Europe, the multiple keys are being used on this structure for the first time in North America.

Transverse pretensioning—As an additional economy measure, the top slab of the bridge is designed to be transversely prestressed with the use of pretensioned strands, thereby reducing the required amount of reinforcing steel and simultaneously providing further

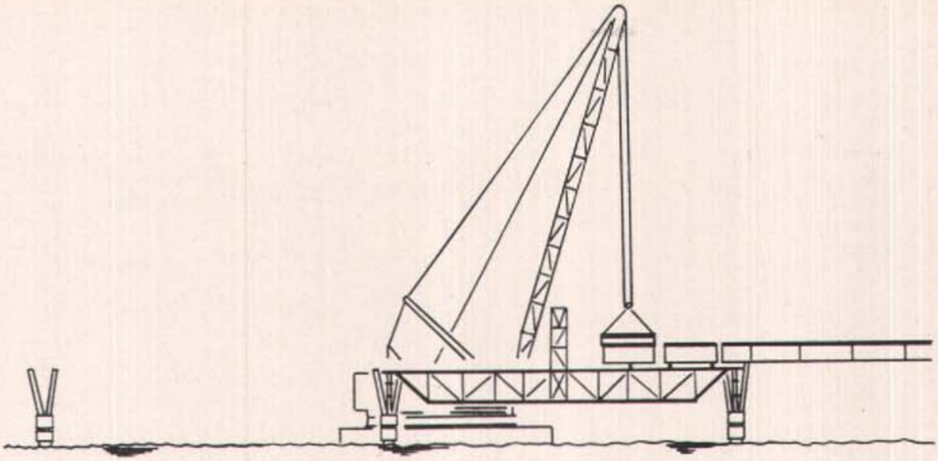


Fig. 1b. Erection truss with precast segments.

protection to the top slab with compressive stresses.

As-cast riding surface—For the first time in segmental construction, the top surface of the segments is designed to be the actual riding surface, with no additional seal or overlay applied. Quality control during precasting and erection is therefore more important and tolerances are reduced below normal values.

Precast V-piers—Twin supports, in the form of V-piers, reduce the effective span length for the structure and result in further economies. Designed to be precast and integrally connected to the box girder, the V-piers actually become a part of the superstructure. The V-piers rest on neoprene bearings on top of the pile caps.

Span-by-Span Erection

As indicated by the name, this method is for the construction of a structure one span at a time; however, it may not be apparent that the method allows each span to be virtually 100 percent completed in a single operation. Once installed, each span of the Long Key Bridge is structurally complete and requires no subsequent post-tensioning operation or temporary support. All other methods of segmental construction require additional stages of post-tensioning for completion; indeed, many require temporary supports for some period of time.

The typical cycle of operation for the span-by-span method is as follows:

1. Precast V-piers are installed on pile caps ahead of the erection operation for the box girder segments.

2. A steel erection truss spanning the 118 ft (36 m) between piers is placed with a floating crane and set to a specified elevation.

3. All segments for the span are set on the erection truss with a crane; segments are delivered on a barge (see Figs. 1a and 1b).

4. A 6-in. (152 mm) thick concrete block is installed between the pier segment of the previous span and the first segment of the span being erected. The block is used to maintain the thickness of a single 6-in. (152 mm) closure joint for each span.

5. One of the tendons is installed on each side of the box girder and 10 percent of the stressing force is applied to hold the segments in position (see Fig. 2).

6. The closure joint is then cast in

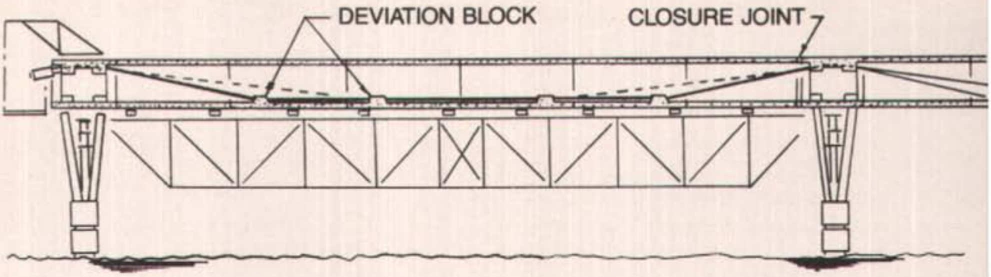


Fig. 2. Post-tensioning operation.

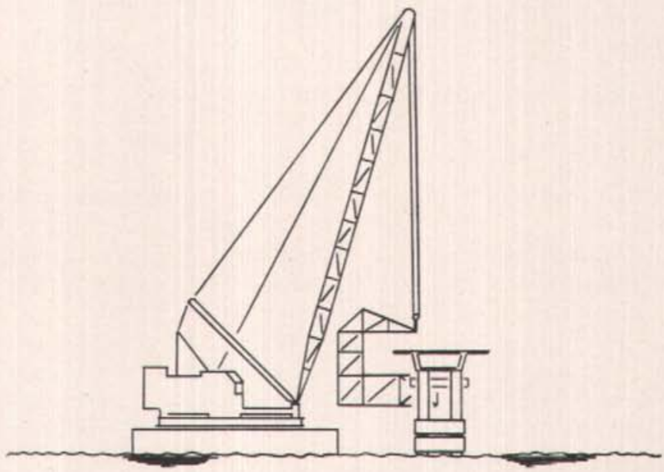


Fig. 3a. Removing erection truss.

Fig. 3b. Placing erection truss in next span.

place, and additional tendons are installed. Connection of the V-pier to the pier segment is made while the closure joint is curing. When the closure has reached a minimum strength of 2500 psi (17 MPa) all tendons are stressed and anchored at their specified full values. Concrete in the closure joints must have the same 28-day compressive strength as the precast segments.

7. When post-tensioning is completed, the erection truss is removed from underneath the segments and moved forward to the next span. Movement is accomplished by lifting the truss with the crane by attaching to a single location on the C-hook, permanently connected to the truss (see Figs. 3a and 3b).

8. Grouting and other finishing operations can be performed after the truss is moved ahead.

Post-Tensioning System

As previously noted, the erection method allows a single-purpose post-tensioning system to be utilized. Installation of the tendons is performed in a single operation at the time of erection, minimizing the time normally required for the complete post-tensioning operation.

The Prescon Corporation was selected to furnish and install the post-tensioning, with the additional tasks of providing all shop drawings for the precast elements and reinforcing steel, consulting for the precast operations, and complete design of the erection truss.

Post-tensioning for the structure utilizes 0.5-in. (13 mm) diameter ASTM A-416 270 ksi (1836 (MPa) low-relaxation strands in tendons containing 19 or 26 strands. Typical spans have two tendons of 26 strands each near both webs, a total of four tendons. Each tendon is anchored in the diaphragm of the pier segment at each end of the span; continuity is provided by overlapping tendons in the diaphragms. Stressing is performed from only one end of the tendons, the open end of the span being erected (see Fig. 4a).

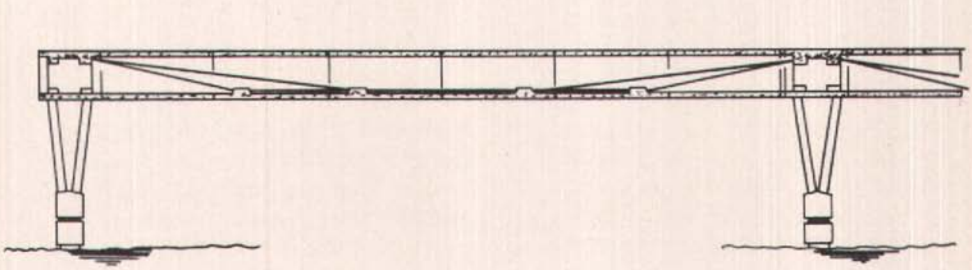


Fig. 4a. Post-tensioning scheme for typical span.

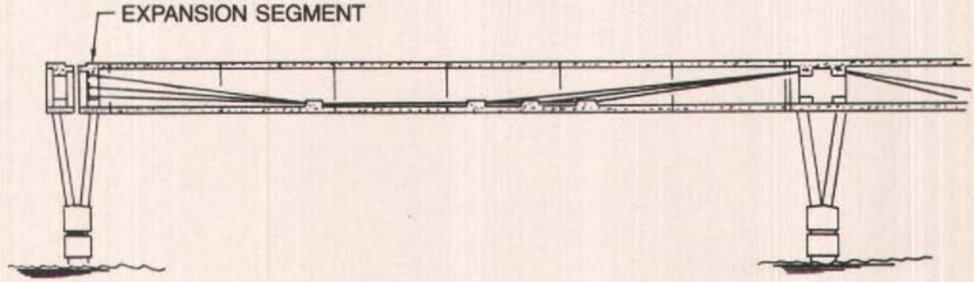


Fig. 4b. Post-tensioning scheme for expansion span.

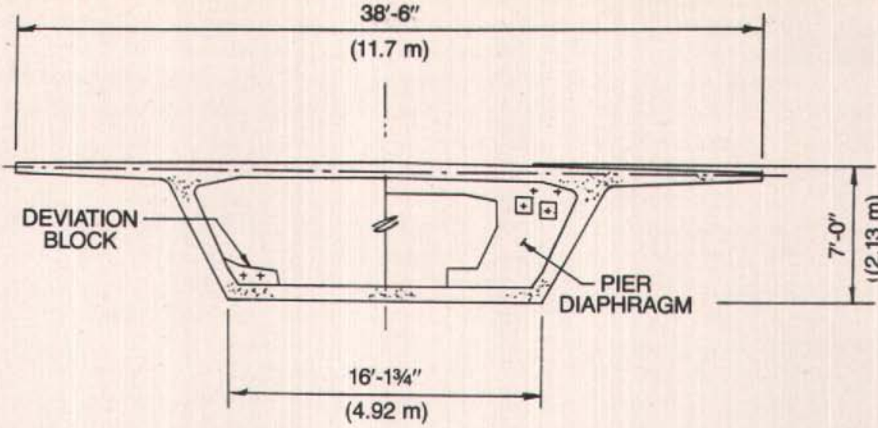


Fig. 5. Box girder cross section.

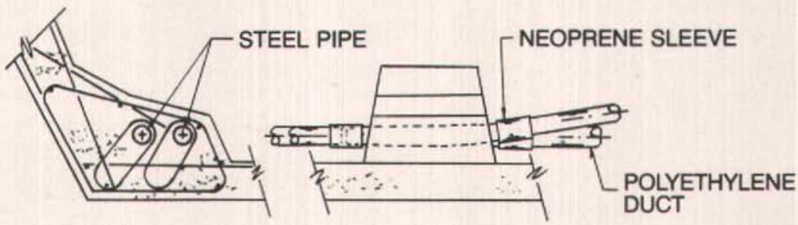


Fig. 6. Detail of deviation block.

The bridge is designed in 944-ft (288 m) units of eight spans; expansion joints are located at the piers with the use of special expansion segments attached to the V-pier. Tendons in the spans adjacent to expansion joints are composed of both 19 and 26 strands each, with a total of six tendons in the span. Due to the configuration of the expansion segments, these tendons are stressed from the opposite end, inside the box girder (see Fig. 4b).

Designed as an unbonded system, but acting semi-bonded, the system of external post-tensioning provides maximum protection for the tendons while allowing optimization of the box girder section. Galvanized steel pipes are embedded in the pier segment diaphragms and deviation blocks; polyethylene (PE) ducts extend between the deviation blocks and from the diaphragm to the first deviation block. Connection of the steel and PE is made with the use of neoprene sleeves. During the precasting operation, anchorages are embedded in the pier segment diaphragms and are joined with the galvanized steel pipes.

Tendons are precut, bundled, and pulled through the pipes, ducts, and anchors. After stressing, the tendons are pressure grouted and the anchors are sealed with a grout cover. Bond of the grout in the steel pipe sections prevents relative movements of tendons and segments, providing a semi-bonded system.

A total of 370 tons (336 metric tons) of post-tensioned strands were required for the structure, with an additional 150 tons (136 metric tons) of pretensioned strand in the top slab. Combined, these quantities represent only 2.3 lbs of prestressing steel per sq ft (10.9 kg/m^2)—a

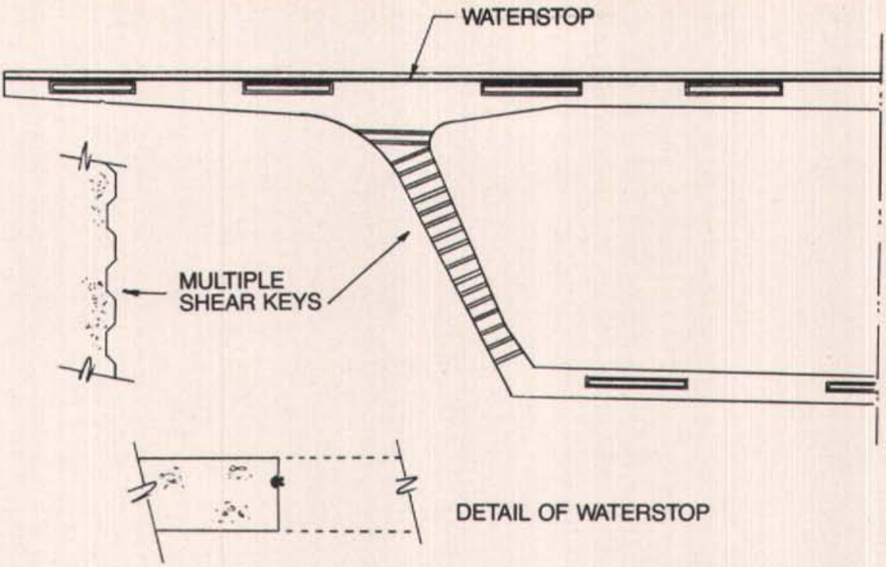


Fig. 7. End view of precast segment showing details of multiple shear keys and waterstop.

very economical value for bridges and an indication of the significant savings offered by the system.

Bridge Details

Functional design and aesthetics have been combined in the bridge and result in an attractive structure completely satisfying all the design criteria. The constant depth section utilizes sloping webs to provide optimum support of the top slab in combination with minimizing bottom slab width. Even the web thickness is varied to optimize the cross section. The cross slope of the top slab is designed to automatically provide the required eccentricity of the non-draped transverse pretensioned strand (see Fig. 5).

Except for deviation blocks at regular locations and diaphragms in the pier segments, the cross section is constant. Typical segments are cast in 18-ft (5.5 m) lengths; pier segments, 9 ft 6 in. (2.9 m). Segments each contain 32 cu yds (24 m^3) of concrete with a minimum 28-day strength of 5500 psi (37.4 MPa); typical segments weigh 65 tons (59 metric tons). All non-prestressed reinforcing steel is epoxy coated for corrosion protection; only 4.2 psf (20.4 kg/m^2) of reinforcing steel is required in typical segments.

Expansion pier segments are cast in two separate pieces, each containing a diaphragm similar to regular pier segments. To simplify handling and erection, the two pieces are temporarily post-tensioned together and are handled as a single unit. The temporary post-tensioning is removed after installation of both spans adjacent to the expansion piers.

Each typical span consists of seven segments; six typical, plus the pier segment. Expansion spans have an additional segment because of the two expansion segment halves, although they are handled as a unit during erection.

The detail of the deviation blocks (Fig. 6) shows the embedded steel pipes and connection to the PE duct. Heavy reinforcement is provided in the deviation blocks to disperse the vertical compo-

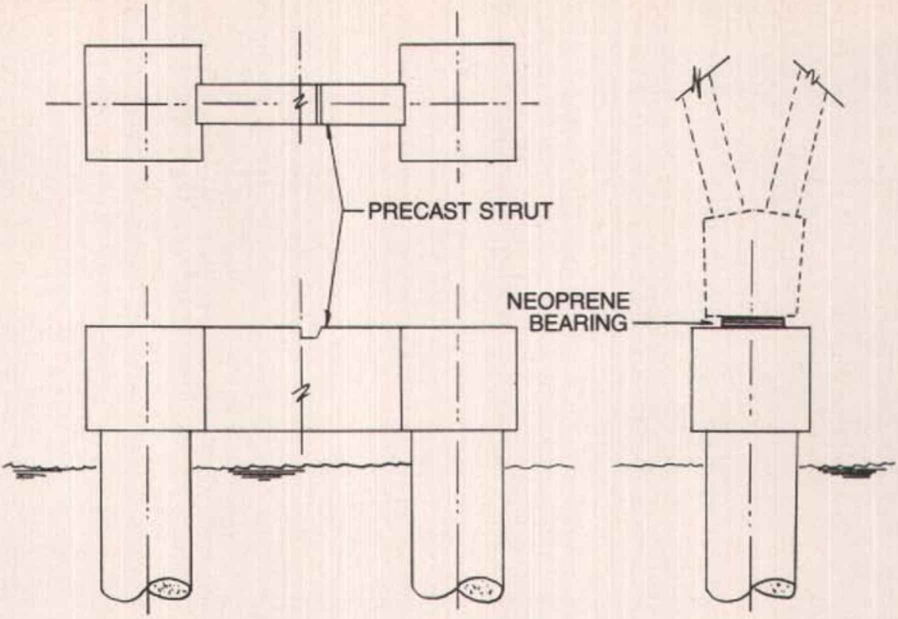


Fig. 8. Substructure details showing precast strut and neoprene bearing.

nent of tendon forces. The location of deviation blocks is computed to provide vertical components equal to dead load shear forces at each location. This allows the spans to be precast and erected with zero camber, simplifying many operations.

Each end of each segment contains multiple shear keys in both webs and slabs (Fig. 7). These keys are formed on one end by the bulkhead of the precasting form and by the matching segment on the opposite end. A small void for a 0.5-in. (13 mm) diameter waterstop is formed across the entire width of the top slab during precasting. A plastic tube is installed and pressure grouted after erection to effect the waterstop.

Substructure

Each pier of the substructure consists of two 42-in. (1.06 m) diameter precast piles placed in a drilled shaft and extending into 15 ft (4.6 m) of the coral rock. A precast strut joins the tops of the two piles of each pier by being cast integrally with a cast-in-place cap on each pile. The lower strut of the precast V-piers rests on a neoprene pad placed on each pile cap (see Fig. 8).

The V-piers are entirely precast and consist of four sloping rectangular legs projecting upward from a lower strut. The legs are cast separately in an horizontal position and are later made integral with the lower strut by dowels projecting from the legs as they are supported within the mold for the lower strut.

Installation of the V-piers is made by placing the units on the neoprene bearings previously set on the pile caps. A pair of temporary bolts is used to hold the V-pier to the pile caps; after the superstructure is installed, the bolts are removed. No other connection is made between the V-piers and the pile caps, except for a transverse shear key between the V-pier strut and pile cap strut at all piers adjacent to expansion piers.

The connection between V-piers and superstructure pier segments is made with dry packed grout and grouted dowels during the erection phase of the

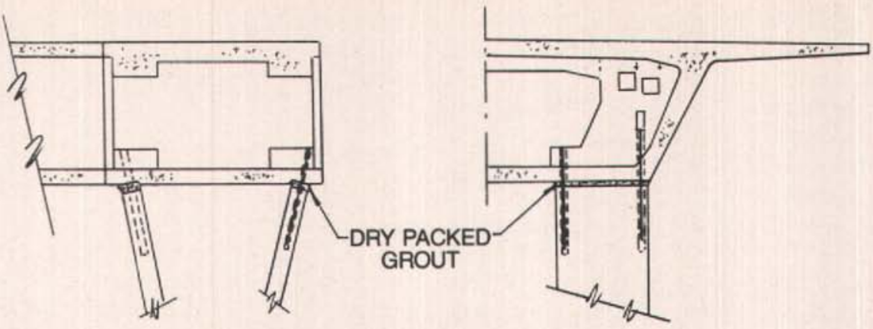


Fig. 9. Connection of V-piers and pier segments.

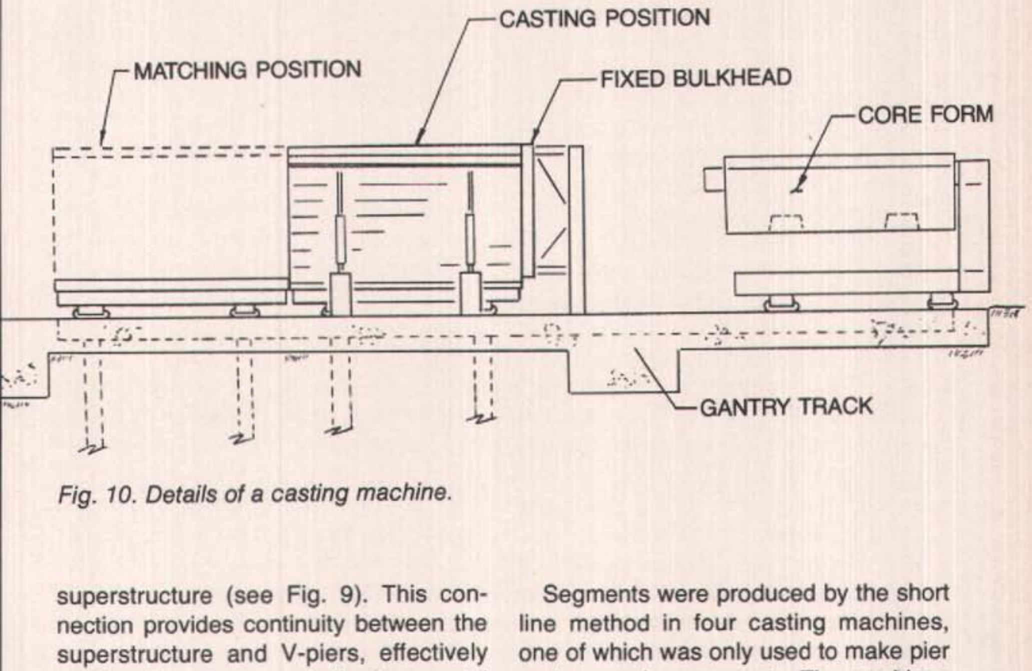


Fig. 10. Details of a casting machine.

superstructure (see Fig. 9). This connection provides continuity between the superstructure and V-piers, effectively making them behave similar to a portal frame.

Because of limited space at the jobsite, the individual precast V-piers are actually stored in place on top of the pile caps.

Precasting Segments

Due to the environmental restrictions and limited available space, the precasting operation was established on the right of way for the western approach to the Long Key Bridge, immediately adjacent to the existing highway pavement.

Segments were produced by the short line method in four casting machines, one of which was only used to make pier and expansion segments. The machines consist of all-steel internal and external forms with two soffit forms each (see Fig. 10).

Michael Construction performed all the precasting operations for the Long Key Bridge and is now casting segments for another structure using the same precasting yard and casting machines.

Both soffit forms and the internal (core) form are mounted on guided rollers riding on steel tracks embedded in the concrete slab foundation. Due to the requirement for zero camber in the spans, the soffit forms and tracks were very carefully adjusted to a horizontal position.

When a segment is cast, it remains on the soffit form, which is rolled to the matching position where no further adjustment is required. The next segment is cast against the first segment before moving it to storage and the soffit form is placed back in the casting position. Elevation and alignment checks are made from fixed control points to insure span alignment and grade.

Casting is simplified by the use of external tendons, eliminating many embedded ducts. The tine finish (small grooves transverse to the top slab), which was specified to improve riding characteristics, is applied to the segments soon after casting while the concrete is still in a plastic stage.

Stressing headers are located between the casting machines to hold the pretensioned top slab strands. Construction is such that strands for any segment can be tensioned or detensioned independent of the other casting machines. Overnight steam curing is applied to the segments since concrete strengths must be at least 4000 psi (27.2 MPa) before releasing the top slab strands, making the curing phase very critical to the casting operation.

Reinforcing steel is prefabricated into cages for quick installation in the casting machines. Concrete is provided by a batch plant located within the precasting yard.

Rubber-tired gantries perform most of the handling functions in the casting yard, including placement of concrete, installation of reinforcing cages, and movement of segments from the casting area to the adjacent storage area. Stacked two segments high, the storage area will hold about 14 spans of segments. This amounts to about 7 weeks of precast production, but only about 3 weeks supply of units cured beyond the required 28-day time.

Due to the use of the as-cast riding surface, no holes are allowed in the top deck and all handling of the segments must be with a special lifting frame.

Erection Truss

Designed to be adjustable to other spans, the erection truss serves as a very capable piece of construction equipment specifically suited to a fast erection cycle. The truss, 118 ft (36 m) in length, weighs 85 tons (77 metric); yet it can be released, moved to the next span, and set to receive segments in less than 3 hours.

An integral C-hook provides a single point hook-up for lifting and moving the truss, which is balanced in all directions for lifting from the single position. Each end of the truss has a hinged section to allow the truss to be moved between V-piers. Temporary steel columns and beams bear on the lower strut of the V-piers and support the four corners of the truss (see Fig. 11). Hydraulic jacks at each corner allow precise elevation control.

The seven segments of a span each rest on three sliding support pads which are Teflon-coated and are positioned on a stainless steel track mounted on the top chord of the truss. As such, the segments can be moved in any direction on the truss with minimum amount of effort; this feature is essential to provide accurate mating of the match cast segment joints.

A camber built into the truss is established such that the top chord is horizontal when the truss is fully loaded with the 450 tons (410 metric tons) of precast segments. Adjustments can be made by the addition of shims on the individual sliding pads to very accurately align the segments. By positioning the pads in the same location for each span, adjustments are rarely required. A permanent post-tensioning tendon is located in the bottom chord of the truss and can be used to adjust its general camber, even when fully loaded.

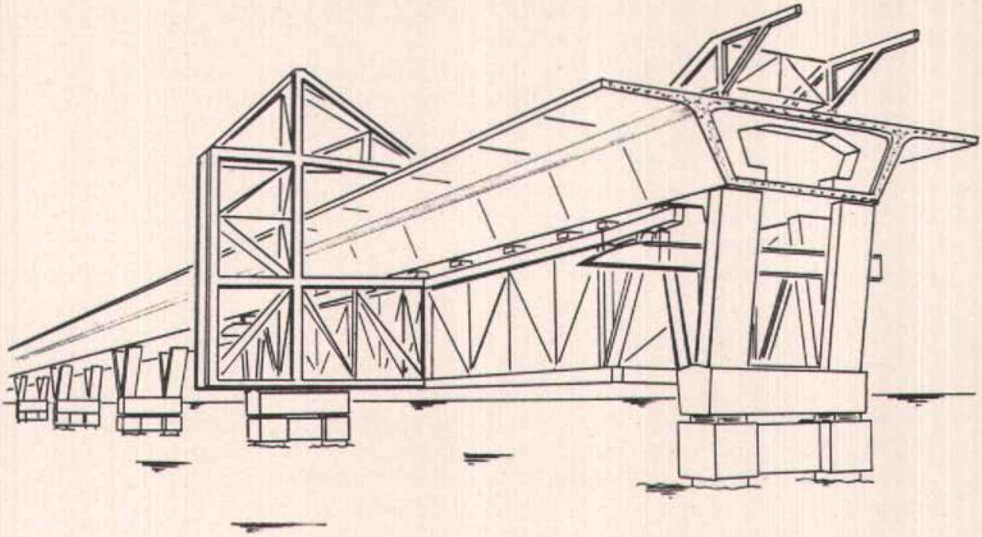


Fig. 11. Erection truss showing progress in segment placing.

Jobsite Performance

The results of the precasting and erection operations have shown conclusively that all the unique features of the Long Key Bridge can be harmonized to produce an economical structure at record speeds with a superior finish and riding qualities.

The precasting yard averaged production of segments at the rate of 2.0 spans per week, i.e., an average of 14 segments per week. The three typical casting machines produced 12 to 14 segments per week, each 18 ft (5.5 m) long; the special form, 2 segments per week.

Erection of the structure was performed at an even more remarkable rate. The first segment was erected in October 1979; completion was on September 25, 1980, some 8 months ahead of schedule. The overall average rate of erection was 2.0 spans per calendar week. After an initial learning period, erection began to average a rate of 2.5 spans per week; 2 spans in one week and 3 spans the next week. During the closing weeks of the project 5 spans were completed in one week.

Although the overall rate was 2.0 spans per week, it may not be readily apparent that the rate is a record erection speed. Various segmental bridges have been constructed with a speed of 4, 6 and even 8 segments per day. However, the rates only apply to those days on which segments are erected. Total elapsed time on the structures, including moving erection equipment, closure strips, continuity post-tensioning, and other operations results in an overall average rate of less than 2 segments per working day.

The Long Key Bridge, with its overall rate of 2.0 spans per week, had an average rate of 2.3 segments per working day, considering 6 days per week. But when it is considered that segments on other bridges are normally only 8 ft (2.4 m) long, the larger segments being installed on this bridge make the overall average rate equivalent to 4.2 segments per day, a record erection pace that will be difficult to match.

Another record set by the contractor that will be extremely difficult to match was the complete erection and post-tensioning of 5 segmental spans in 6 consecutive calendar days, with a single shift. That amounts to 590 ft (180 m) of completed bridge, the equivalent of 13 segments per day on a sustained basis.

Since all segments for a typical span are usually placed on the erection truss in a single shift, the installation of 14 equivalent segments per day occurred routinely. It is anticipated that some structures will be built similarly with higher construction rates. The single floating crane used on this project not only erected segments but moved the erection truss, installed V-piers, and loaded segments from storage onto barges.

Not only did the construction proceed at a record pace, but also the assembled spans were produced within very tight tolerances and are providing excellent riding quality. Because of the as-cast riding surface, the tolerance in offset between joining segments was established as $^3/_{16}$ in. (5 mm); actually results were much better. An indication of the quality is that the tubes used as waterstops were installed in the match cast joints after the spans were erected; it was accomplished in each joint by pulling the tube through the single 0.5 in. (13 mm) void formed by a half-void in each segment.

Closing Remarks

Long Key Bridge has proven that the method of span-by-span erection, with all of its associated design features and cost benefits, can work. It can be expected that future applications of the system will be further developed and applied to many bridges, with similar or even better results. A new field of bridge construction has been opened, with the possibility of radically changing many concepts and previous constraints. Precast prestressed segmental construction does indeed have a bright future.

Credits

Figg and Muller Engineers, Inc., Tallahassee, Florida, designed the complete bridge and furnished construction administration for the project.

Michael Construction Co., Inc., Chattanooga, Tennessee, was general contractor and performed precasting and erection of the structure.

The Prescon Corporation, San Antonio, Texas, furnished and installed the post-tensioning system, in addition to providing shop drawings for all precast elements, complete design of the erection truss, and consulting for the precasting operation.

Concrete Forms Corp., Chattanooga, Tennessee, furnished the four casting machines.

The design and construction of Long Key Bridge was under the jurisdiction of the Florida Department of Transportation (with assistance from the Federal Highway Administration) and the bridge is owned by the State of Florida.

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