Special Report

Segmental Bridge Construction in Florida — A Review and Perspective

by

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SYNOPSIS

This paper offers an overview of the precast concrete segmental bridges designed and built in the state of Florida during the last ten years. The article summarizes various statistical structural parameters, segment manufacturing and erection methods, construction times, costs, and reviews problems typically encountered. Also included is a discussion of current industry and nationwide design and construction practices and some suggestions for possible improvements.

CONTENTS

1. INTRODUCTION

Modern concrete segmental bridges were made possible as a result of postwar developments in post-tensioning systems and materials technology. This was spurred on by the need for much reconstruction and new infrastructure in Europe following World War II. After some initial development in Europe, these systems were introduced into North America in the '60s and '70s and have now become quite commonplace.

Early post-tensioned concrete segmental bridges were cast-in-place in cantilever using traveling formwork with spans of up to 400 ft (122 m). This remains the preferred method for large spans such as the Houston Ship Channel [at 750 ft (229 m)] and the planned concrete alternate for the Acosta Bridge in Jacksonville [at 630 ft (192 m)].

Precast segmental bridges were a natural development for efficiency, standardized mass production, speed of erection, the elimination of expensive formwork in deep valleys and over navigable waterways and, particularly, to afford solutions for restricted construction access in congested urban or environmentally sensitive areas. The most notable example of the latter is the Linn Cove Viaduct[1] on Grandfather Mountain in North Carolina. This bridge was constructed entirely from the top, including piers and foundations, in order to preserve the delicate environment of this scenic region. It is the "precast" type of segmental bridge that has found many applications in Florida over the last 10 years. So far, 31 major structures have been built, including the Sunshine Skyway Bridge.

2. PRECAST SEGMENTAL BRIDGES

Precast segmental bridges are so called because they are made of individual precast units or "segments" carefully manufactured in a precast concrete plant, either on or off the site. The segments are later erected and secured together by longitudinal post-tensioning to form each span or cantilever.

They fall into the following general categories according to their method of construction:

(a) **Span-by-Span** — Where all the segments of one span between piers are erected on a special supporting truss or gantry and are longitudinally post-tensioned together after making small cast-in-place closure joints at one or both ends next to the pier segments. Examples include the Long Key and Seven Mile Bridges in the Florida Keys (Figs. 1 and 2)[2,3] and the high level approaches to the new Sunshine Skyway Bridge over Tampa Bay.[4,5]

(b) **Balanced Cantilever** — Where segments are erected sequentially in cantilever on each side of an initial segment placed on top of the pier. Stability is provided by a temporary tower or other support near the permanent pier. Cantilevers are joined by cast-in-place closures at midspan. There are many examples of this throughout the state, including Ramp I at the Florida Turnpike/I-75 Interchange (Fig. 3).[6]

(c) **Progressive Cantilever** — Where segments are erected in cantilever in one direction, starting at one end of the bridge and progressing over all the piers in sequence. Additional intermediate temporary piers or towers with cable stays are needed to facilitate construction in cantilever from one pier to the next. Examples include the Linn Cove Viaduct in North Carolina and the Fon-

Fig. 1. Long Key Bridge — A precast segmental, post-tensioned, span-by-span structure. (Courtesy of Figg and Muller Engineers Inc., Designer)

Fig. 2. Seven Mile Bridge — A precast segmental, post-tensioned, span-by-span structure. (Courtesy of Figg and Muller Engineers Inc., Designer)

tenoy Bridge in France.[7]

In all these systems, the precast segments are usually made in a special form or "casting cell" where a new segment is cast against its older neighbor to achieve a perfectly mating or "match cast" joint. To date, only the "short line" or "single cell" casting machine has been used (as opposed to the "long line bed" system) in Florida. In the long line bed system, the entire soffit of the bridge is laid out in the casting yard and each segment is made in turn in its proper place.

When erected in the bridge, the joints between segments are coated with epoxy to fill any surface imperfections and provide a tightly bedded joint. This also helps to seal and protect internal post-tensioning tendons. Because external post-tensioning tendons were used in the first span-by-span bridges in the Florida Keys, the segments were not jointed with epoxy but were left dry. However, all subsequent structures, including the similar span-by-span approaches to the Skyway, have epoxy filled joints between segments.

Temporary post-tensioning bars are used to secure each segment tightly to its neighbor prior to installing and stressing the permanent longitudinal post-tensioning tendons which provide the structural capacity and continuity of the superstructure. Schematic illustrations of typical span-by-span and balanced cantilever construction are shown in Figs. 4 through 8.

Other types of bridge construction systems are sometimes referred to as "segmental." These include:

- Incremental launching
- Partial precast and cast-in-place construction
- Post-tensioned segmental I-girders
- Cast-in-place post-tensioned bridges
- Precast wet joint segmental

These systems share many common features, especially post-tensioning and special erection systems of falsework, towers or travelers, etc. However, they are different in techniques from precast segmental bridges and, with the exception of post-tensioned I-girders, have found few applications in Florida.

Fig. 3. Ramp I — A precast segmental, post-tensioned, balanced cantilever viaduct. (Courtesy of Beiswenger Hoch and Associates, Designer)

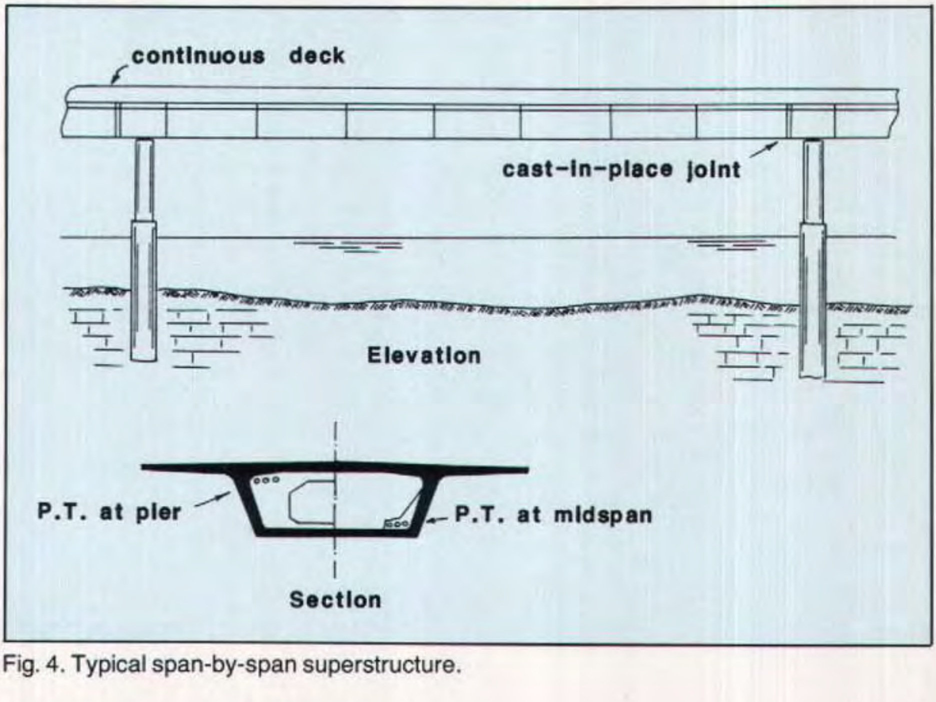

Fig. 4. Typical span-by-span superstructure.

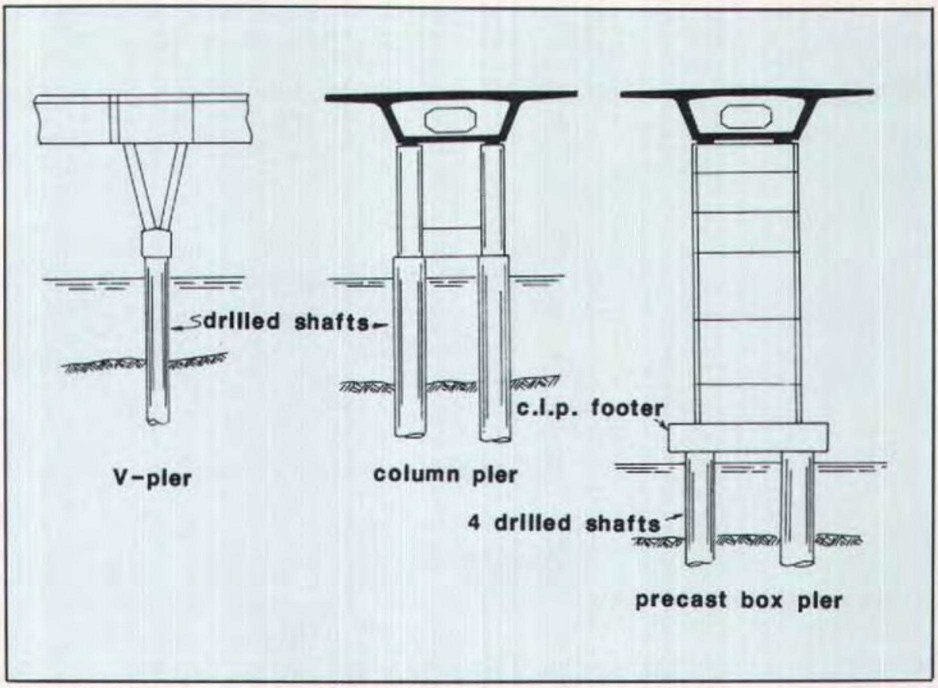

Fig. 5. Typical span-by-span substructures.

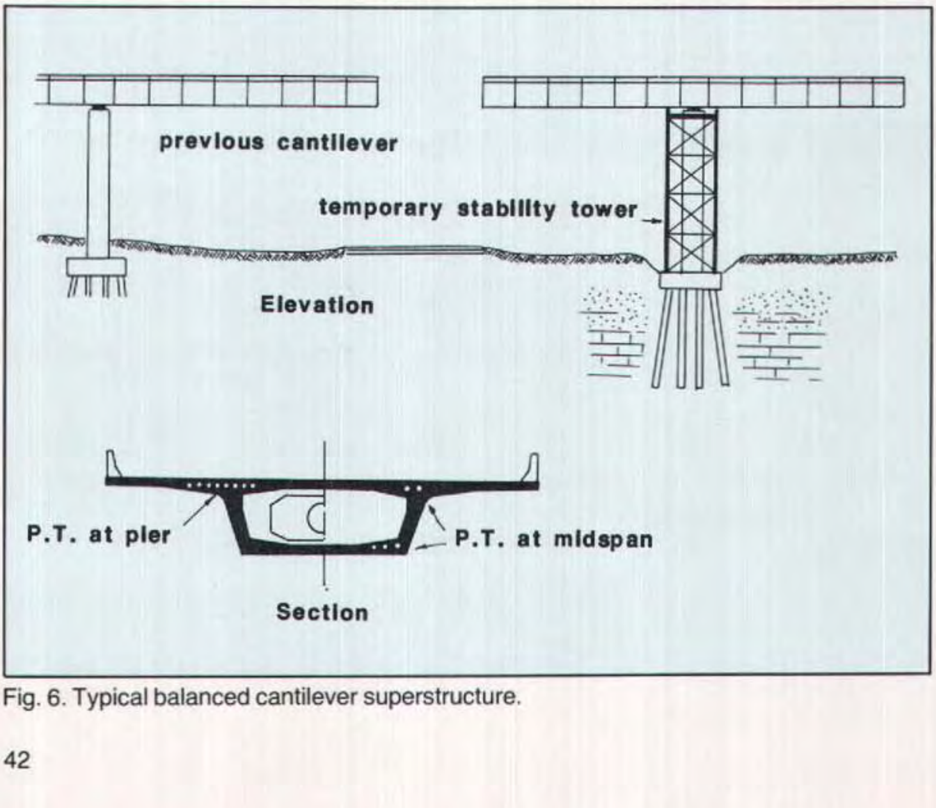

Fig. 6. Typical balanced cantilever superstructure.

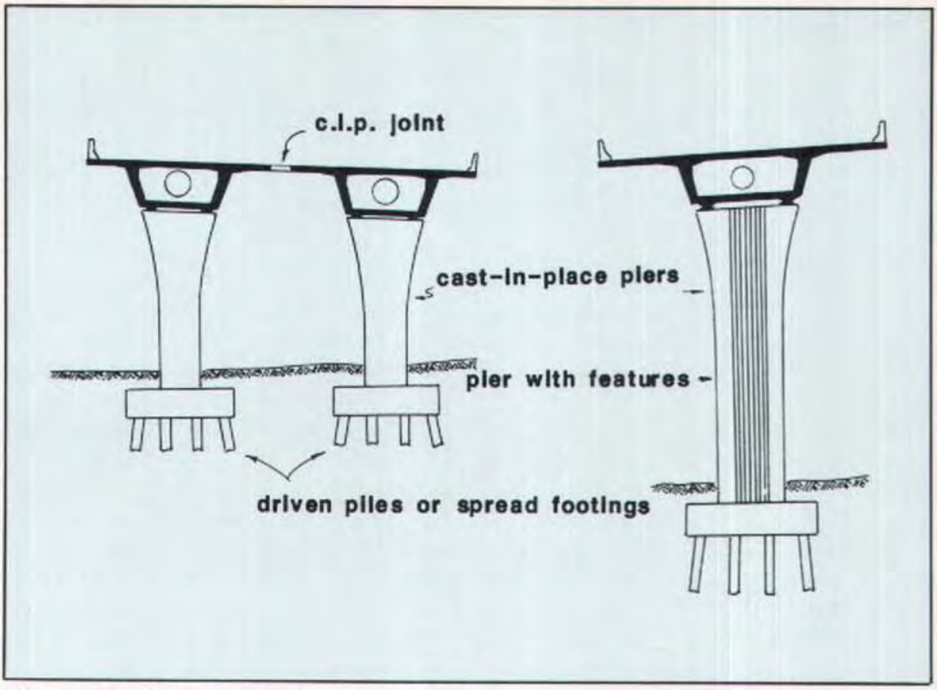

Fig. 7. Typical balanced cantilever substructures.

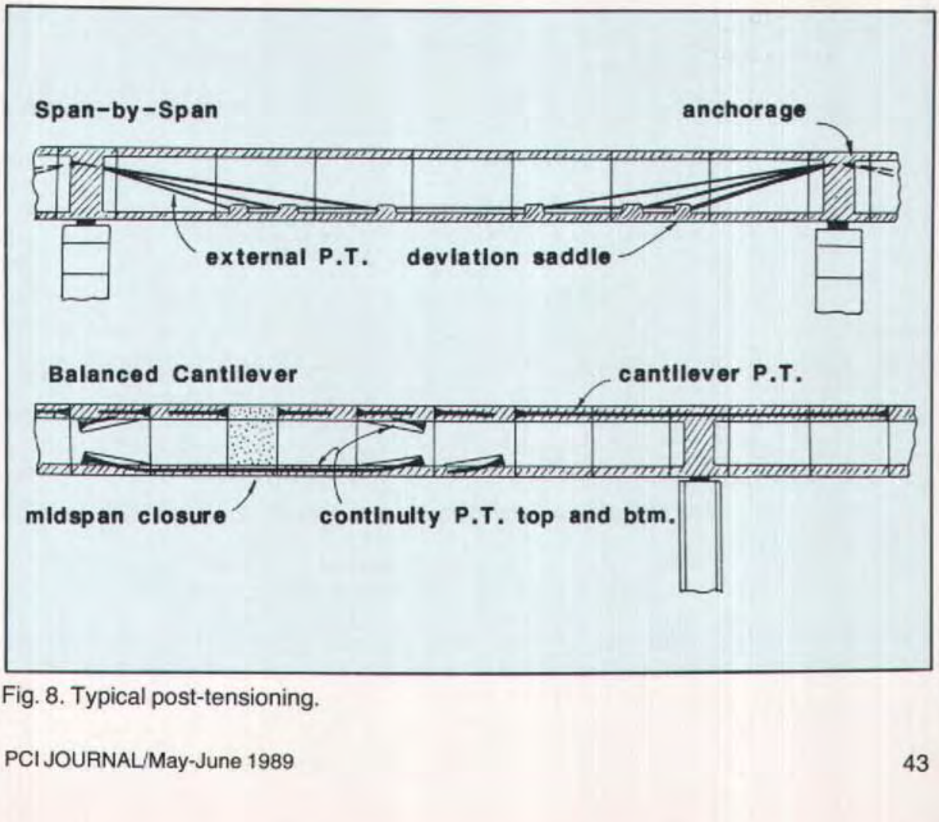

Fig. 8. Typical post-tensioning.

3. FLORIDA'S SEGMENTAL BRIDGES

The Long Key Bridge was the first precast segmental bridge constructed in Florida; since then, a total of 31 bridges have been built, including the cable stayed Sunshine Skyway Bridge over Tampa Bay (Fig. 9). Several more have been and are being designed. [The Sunshine Skyway is an exceptional structure in its own right and will not be discussed in detail here. However, certain information and experience from the Skyway project have been incorporated — particularly that which pertains to the high level span-by-span approaches which are typical of other segmental, rather than cable stayed, construction. Also, the Sunshine Skyway main span unit incorporates balanced cantilever spans of 240 ft (73 m) on either side of the cable stayed sections. This is a somewhat unique application which would not necessarily reflect costs or other data typical of a normal cantilever of this span.]

Generally, Florida's segmental bridges are either span-by-span or balanced cantilever. Typical features are highlighted in Table 1. In general, span-by-span construction has been used only on straight structures, over water with spans between 118 and 143 ft (36 and 44 m). For larger spans up to 225 ft (69 m) and especially for curved interchange viaducts on land sites, balanced cantilever has been used.

Substructure and foundation types follow a similar trend, with lighter precast and cast-in-place substructures in span-by-span applications, as opposed to more massive cast-in-place substructures required by balanced cantilever construction. The difference arises from the span lengths and the fact that cantilever construction usually requires significant out-of-balance erection effects be carried into the foundations. There is no out-of-balance effect with span-by-span construction, so the foundation loads and moments are much less. Also, frequent economic use has been made of drilled shafts in most of the span-by-span structures as opposed to more commonly used driven piles. Although partly dictated by site and ground conditions, either foundation system could have been used. This also reflects the different philosophies of designers.

4. STRUCTURAL PARAMETRICS

Structural economy in materials and efficiency has been achieved in segmental construction from the fundamental principle of continuity in superstructures as opposed to traditional simple span girders. Continuity permits a general reduction in structural dead load with savings in substructures and foundations, particularly in span-by-span systems.

The use of continuous construction as a means to structural efficiency and economy is also applied in other structural systems such as steel plate and box girders and the newly developed Florida bulb tee precast post-tensioned girder system, recently introduced on the Eau Gallie[8] and Howard Frankland Bridges.

Including the Skyway approaches, five span-by-span structures, totaling over 2,600,000 sq ft (241,000 m^2) of bridge deck, have been built. Twenty-six balanced cantilever bridges, representing another 1,400,000 sq ft (130,000 m^2), have been built. These were built using 7500 precast deck segments and several hundred precast pier segments (Tables 2, 3 and 4).

Fig. 9. Sunshine Skyway Bridge — A precast segmental, post-tensioned, cable stayed cantilever bridge with span-by-span high level approaches. (Courtesy of Figg and Muller Engineers Inc., Designer)

Table 1. Precast segmental projects.

Projects	No. of bridges	Balanced cantilever	Span-by-span		Principal features
Long Key	1		•	31 built	Span-by-span Over water Straight Precast/cast-in-place substructures Mostly drilled shafts 5 built = 2.6 M sq ft 1 bid not built 1 in design
Seven Mile	1		•		
Niles Channel	1		•		
Channel Five	1		•		
Ramp I	1	•			
Skyway Approaches	1		•		
I75/I595-1	5	•			
Palmetto	5	•			
Airport	4	•			
441/I595-M	2	•			
I75/I595-2	9	•			Balanced cantilever Interchange sites Curved Cast-in-place substructures Mostly driven piles 26 built = 1.4 M sq ft 10 bid not built Several in design
I95/I595-DEF	8	•		11 bid but not built	
South Fork New River	2	•			
Howard Frankland	1	•	•		
Port of Miami	1	•		In design	
Edison	1		•		
Golden Glades	n	•			

Table 2. Superstructure parametrics.

Parameters	Span-by-span	Balanced cantilever
Span ranges, ft	118 - 143	71 - 224
Box depth, ft	7 - 8	6.5 - 9.3
Segment weight, tons		
Typical	64 - 75	38 - 58
Pier	40 - 83	48 - 98
Abutment/expansion joint	34 - 52	25 - 72
Equivalent solid concrete thickness, ft	1.3 - 1.6	1.6 - 2.0
Reinforcing bars, psf	4.5 - 9.4	8.4 - 18.0
Transverse post-tensioning, psf	0.5 - 0.8	0.6 - 1.1
Longitudinal post-tensioning, psf	1.5 - 2.8	3.6 - 5.5

Metric (SI) conversion factors: 3.28 ft = 1.00 m; 1 ton (US) = 0.91 tonne; 1 psf = 4.89 kg/m^2.

Table 3. Substructure parametrics.

Parameter	Span-by-span	Balanced cantilever
Span ranges, ft	118 - 143	71 - 224
Height ranges, ft	20 - 152	24 - 97
Ratio of $\frac{\text{solid substructure}}{\text{spanned void}}$, (percent)	0.94	2.02
Reinforcing bars in substructure, lb per cu yd	135	154
Post-tensioning in substructure, lb per cu yd	7.3	0
Foundations		
Drilled shafts, percent	84	0
Driven piles, percent	16	80
Spread footings, percent	0	20

Metric (SI) conversion factors: 3.28 ft = 1 m; 1 lb per cu yd = 0.59 kg/m^3.

In span-by-span construction, most decks are 38 to 43 ft (11.6 to 13.1 m) wide for two lanes of traffic with shoulders and barriers. Superstructure segments are typically 18 ft (5.5 m) long and 7 to 8 ft (2.1 to 2.4 m) deep for spans from 118 to 143 ft (36 to 44 m) and weigh about 65 tons (59 tonnes) each.

The average equivalent solid concrete deck thickness is about 1.4 ft (426 mm) and the weight of reinforcing bars is between 4.5 and 9.41 psf (22 and 46 kg/m^2), depending upon whether transverse post-tensioning is used or not. However, higher quantities of reinforcement in more recent projects are a reflection of more stringent design criteria introduced by Florida's Department of Transportation in 1984.

When used, transverse post-tensioning averages 0.70 psf (3.42 kg/m^2). Longitudinal post-tensioning ranges from 1.5 to 2.8 psf (7.3 to 13.7 kg/m^2). This is primarily a function of

Table 4. Casting operations.

Structure	Number of superstructure segments	Number of casting cells		Average sustained production rate,* segments per week
		Typical	Other	
Long Key	734	3	1	17
Seven Mile	2154	5	1	28
Niles Channel	276	3	1	17
Channel Five	299	3	1	17
Ramp I	201	2	1	6
Skyway Approaches	584	2	1	10
Skyway MSU	333	2	1	5
I75/I595-1	567	2	1	10
Palmetto	658	5	2	24
Airport	286	2	1	12
US 441/I595	385	2	1	11
I75/I595-2	1316	7	3	32

*After mobilization and learning period.

Fig. 10. Seven Mile Bridge — Precast vertically post-tensioned, segmental box piers.

the span lengths but also reflects a little more conservatism in later structures.

In balanced cantilever construction, the segment widths are typically around 42 ft 9 in. (13.03 m) at the top slab for single boxes with two lanes, shoulders and barriers, and up to 2 x 28 ft (2 x 6.56 m) for twin boxes in wider bridges (Fig. 4). Segment weights range from 25 to 98 tons (23 to 89 tonnes) but are typically 50 to 60 tons (45 to 55 tonnes). Equivalent solid concrete deck thicknesses range from 1.56 to 2.04 ft (475 to 622 mm), although this does not necessarily match spans which range from 120 to 225 ft (36.6 to 68.6 m).

Reinforcing bar steel varies from 8.4 to 18.0 psf (41.1 to 88.0 kg/m^2) with a typical range from 9 to 14 psf (44.0 to 68.5 kg/m^2). Transverse post-tensioning typically averages about 0.85 psf (4.2 kg/m^2). Longitudinal post-tensioning amounts vary from 3.6 to 5.5 psf (17.6 to 26.9 kg/m^2). The variations in reinforcing bar and post-tensioning quantities reflect both structural requirements for the spans and more conservatism in the FDOT design criteria of 1984. Also, some structural depths were restricted by highway clearances dictating less efficient sections, thus requiring high reinforcing bar and post-tensioning content.

A review of substructure data shows clearly how much lighter substructures are in general for span-by-span as opposed to cantilever construction — for reasons discussed in Section 3. Compare, for example, the average ratio of solid substructure to spanned void volumes for span-by-span at about 0.94 percent and cantilever construction at about 2.0 percent, i.e., almost a 1:2 variation.

Vertically post-tensioned substructures have only been used on precast box piers to date, for the Seven Mile (Fig. 10), Channel Five and Skyway Bridges. These are typically efficient, high level span-by-span structures.

5. CASTING YARD OPERATIONS

On all projects but one, the prime contractor elected to produce the segments himself by establishing a precast yard at or near the site. In only one case, that of the Seven Mile Bridge, was the prime contractor already in the precast business. This contractor had his own production facilities in Tampa Bay, from where the segments were barged to the Florida Keys.

Casting facilities have been geared to the overall size of the project and contract period on an anticipated peak production rate of one typical segment per day per casting cell and one pier or abutment type segment every 2 or 3

Fig. 11. Pier segment in casting cell — I75/I595 Phase 2 Interchange.

days. In general, these rates have been achieved.

The normal complement of casting machines was two to four cells for typical segments and one for pier segments (Fig. 11). The expansion joint, abutment or other nonstandard segments were usually made by adapting a typical casting cell with wooden bulkheads or similar formwork.

Generally, it would require about 3 to 4 months to establish the casting yard facilities. This was followed by a few weeks of learning by the crews and modifications and improvement to the facilities until a consistent production rate was achieved.

It should be emphasized that projects have run considerably smoother where the contractor engaged experienced personnel or sought advice in the planning and acquisition of his casting facilities. Also, this was especially true when good quality forms were used.

Concrete has been produced by batch plants at the casting yard and/or delivered by truck, depending upon availability and prices in the locality. Segments have rarely, if ever, been lost due to failure of concrete production and delivery.

Travel lifts have been most efficient for handling segments in the casting yard. Segments have been lifted either by special frames attached by thread bars through the top slab, C-frames, or slings. Often, these devices have been used later at the site for erection (Fig. 12).

Fig. 12. Balanced cantilever segment erection by crane at US 441/I595 Interchange. (Volker Stevin, Contractor)

Segment storage sometimes required double stacking. In these cases, special care had to be taken to avoid damage to the bottom segment, including warping through uneven supports.

6. REJECTED SEGMENTS

Experience shows that success in segmental bridge construction depends almost entirely upon the casting operations.

Attention to workable and constructible details, good planning of casting work, and quality workmanship pay dividends. This is illustrated in Table 5, which lists rejected segments and summarizes the various reasons for rejection. The highest attrition has been on projects built, usually as a first time, by inexperienced groups. Even experienced contractors cannot avoid some loss. This situation is evidently a statistical phenomenon. It appears that a reasonable loss rate should not exceed 0.5 percent.

Table 5. Rejected segments.

Project	Number lost	Percent lost
Long Key	4	0.5
Seven Mile	3	0.2
Niles Channel	0	0
Channel Five	1	0.4
Ramp I	1	0.5
Skyway Approach	3	0.5
Skyway Main Spans	1	0.3
I75/I595-1	18	3.2
Palmetto	19	2.9
Airport	0	0
US 441/I595	1	0.3
I75/I595-2	3	0.3

Summary of reasons for rejecting segments:

- Voids/honeycombing*
- Post-tensioning ducts displaced*
- Reinforcing bar post-tensioning conflicts*
- Weak forms*
- Dimensional tolerances
- Geometric alignment control
- Improper handling/storage
- Curing/thermal
- Low strength
- Damaged shear keys
- Accident
- Weather

*Majority of losses for these reasons.

7. ERECTION OPERATIONS

Various erection systems have been used in Florida (Table 6). These have fallen into the broad categories of ground based crane for cantilever erection at interchange sites and truss or gantry for span-by-span erection over water. The latter was the first method introduced with the construction of the Keys Bridges. An underslung truss was used for Long Key, Niles Channel and Channel Five, and an overhead gantry for Seven Mile (Fig. 13).

Fig. 13. Overhead gantry for span-by-span erection at Seven Mile Bridge.

This technique was subsequently used for the Skyway approaches. Since all cantilever structures except the main span unit of the Skyway have been over land, regular cranes have been the most suitable. The balanced cantilevers of the Skyway main span unit were erected by beam and winch devices with stability being provided by steel girders spanning to the previously erected structure. These devices were also used for the main span segment erection (Fig. 14). An incidental use of the beam and winch system was required on the I75/I595 Phase 2 project to erect some segments underneath an existing higher level bridge.

Rates of erection have been geared to the project size and contract duration. After a few weeks of learning period, span-by-span construction typically ran at three spans per week and in some cases, at Long Key and Seven Mile,

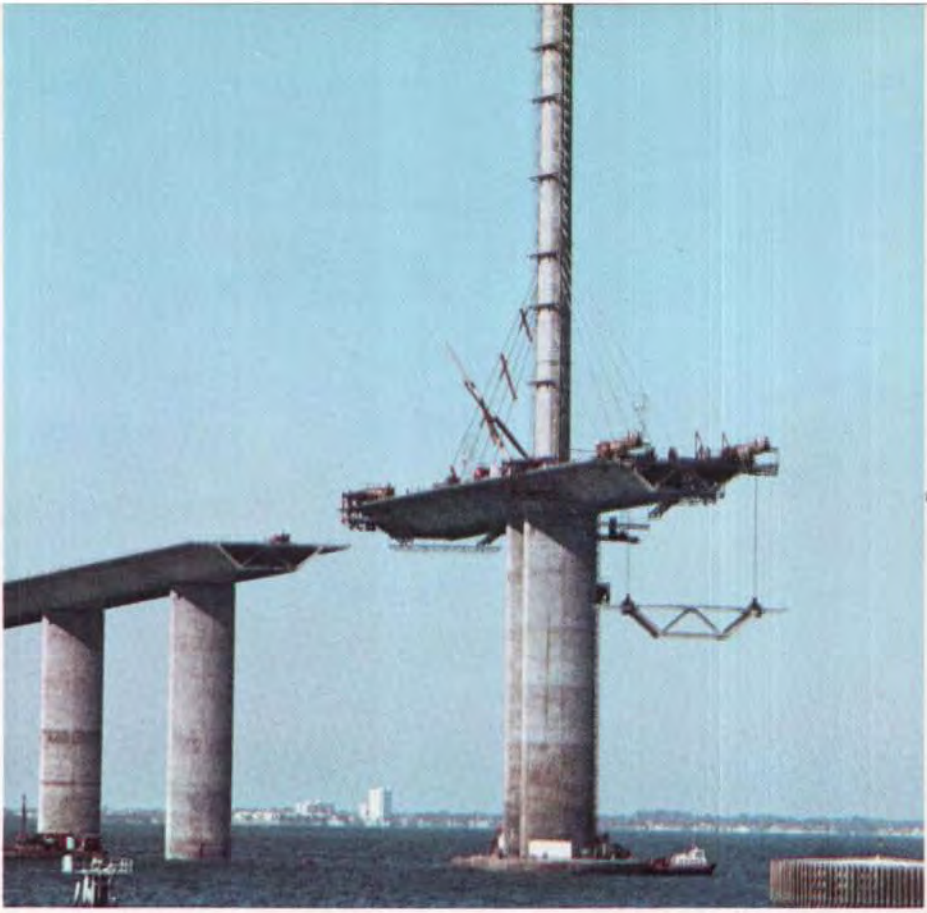

Fig. 14. Main span segment erection at Sunshine Skyway using beam and winch equipment.

Table 6. Erection methods.

Parameter	Span-by-span	Cantilever
Site	Water	Land
Delivery	Barge	Lowboy
Erection equipment		
Truss plus floating crane	33 percent*	
Overhead gantry	67 percent*	
Crane on ground		91 percent*
Beam and winch		9 percent†
Stability towers	Not required	Used
Falsework	Not required	Used
Learning period	3 to 4 weeks	Varies
Sustained rate	3 spans per week	4 to 6 segments per day per cantilever (2 cranes)

*This percentage is based upon the total number of segments erected per bridge type.

†This figure includes the segments in the Sunshine Skyway main spans.

Fig. 15. Balanced cantilevers under construction at US 441/I595 Interchange. (Designer: Greiner Engineering Sciences Inc.)

achieved one span per day, i.e., up to five spans in one week.

Balanced cantilever erection rates have varied widely. On at least two projects, Ramp I and US 441/I595, the rate of erection was not so critical to overall completion and it proceeded well, on time and with very few minor complications. Other cantilever projects encountered slow learning periods and difficulties through poorly aligned post-tensioning ducts, geometric alignment control, etc. However, on more recent projects, such difficulties were avoided and erection progressed rapidly, particularly at the US 441/I595 and I75/I595 Phase 2 interchanges.

The former project involves two very long curved segmental cantilever viaducts and is approximately 6 months ahead of schedule (Fig. 15). On the latter project, which involves nine similar segmental bridges, the contractor achieved a substantial incentive bonus for opening a section ahead of schedule. At the time of this writing, he is likely to finish the entire interchange 9 months ahead of schedule.

8. SOME TYPICAL PROBLEMS

The following problems have been encountered to some extent at various times. Fortunately, their recurrence is far less likely today. While the following problems are cited, it must be remembered that they are not exclusive to segmental construction. Many of these (and other) problems occur in other types of construction. In the construction industry as a whole, problems are not unusual and they are routinely resolved.

Honeycombing — This occasionally occurred in web walls and congested reinforcing bar zones but was usually cosmetic and easily repaired by cutting back to sound concrete and filling with high strength, nonshrink, cement mortar or fine aggregate concrete. Only on rare occasions was it so severe as to require engineering analysis and/or total rejection of the segment.

Damaged shear keys — Occasional damage or loss of whole keys might occur during stripping or handling. Usually, this happened with new crews early in the projects, and it was avoided by taking more care. In the Keys Bridges, the loss of two or three shear keys was determined not to be detrimental to erection and they were repaired by dry packing after erection but before post-tensioning.

Top riding surface finish — A fairly good riding surface was achieved in all the Keys Bridges as a result of accurate workmanship in finishing the top surface in the casting yard. However, some subsequent cantilever bridges had lesser quality and required grinding. The poor quality surface was due to improper attention to finishing work in the casting cell. A good quality riding surface has been achieved on both the major projects nearing completion at US441/I595 and at I75/I595 Phase 2. A rotary screed (Fig. 16) was used at the former project and a straight vibratory screed at the latter project (Fig. 17). In both cases, the screed was followed by the use of a straightedge and a light application of bull floats. Skilled concrete gangs were employed on both of these projects.

Concrete materials — Generally, these have been satisfactory and there have been no more problems with quality control than with other methods of construction.

Misaligned post-tensioning ducts — Problems with misalignments have not arisen in span-by-span construction using external tendons passing through deviation saddles and anchor zones. There have been some problems in cantilever construction which caused excessive friction and consequently, reduced elongations or, in the worst cases, wire breakage. These were attributed to:

- Inadequate duct supports, stiffeners and seals
- Inaccurate placement of ducts
- Trapping ducts between reinforcing bars
- Damage from concrete placement and consolidation
- Detailing too tight

Blocked post-tensioning ducts — These were due to either inadequate seals against cement grout during concreting or from crossflow of post-tensioning grout after stressing. (Both are avoidable with care and attention to workmanship.)

Handling — In the Keys, a few box pier segments were lost when a lifting cable failed and one segment fell on others in storage in the casting yard. A main span segment of the Skyway was lost due to a failure of the gantry.

Stacking and storage — Improper double stacking of a pair of segments for Seven Mile caused cracking and the rejection of one of them. The problem was caused by uneven settlement. Current practice permits double stacking under controlled conditions using a three point support, two under one web and one in the center of the other web. An analysis of the loaded segment must show acceptable stresses.

Cracking — Occasionally cracking has occurred due to curing temperatures or shrinkage. Cracks of a structural type have sometimes occurred for which there was usually an explanation. For example:

- Spalls due to concentrated local post-tensioning effect from anchorages
- Flexural cracks due to inadequate bond on epoxy coated reinforcing bars

Epoxy coated reinforcing bars — These have exhibited an inability to

Fig. 16. Use of a rotary screed, followed by straightedge and light application of bull floats for a good finish.

Fig. 17. Use of a vibratory screed, followed by straightedge and light application of bull floats for a good finish.

bond to concrete and control shrinkage and flexural strains between the reinforcing bars and the concrete. (Evidence for this comes from field experience and observations on various structures, some being segmental bridges since epoxy bars were first used in these. This also involves questions about the adequacy of the corrosion protection, which is still under investigation by the Department of Transportation and beyond the scope of this paper.)

Alignment and cambers — There have been no difficulties with alignments and cambers in span-by-span construction. Horizontal and vertical alignment errors were encountered, but satisfactorily resolved, in some cantilever construction. On one occasion the contractor made the last two closures out of sequence, resulting in a cusp in the vertical profile.

Weak forms — Some forms could not withstand concreting operations and gave way at joints, causing voids and other problems. This was cause for rejecting several segments on one project and the problem was solved only by strengthening the forms. Forms must be robust and able to withstand concrete pressures and much abuse; joints should be good with reliable, tight seals. Weak, flexible forms result in cement paste leakage, honeycombing, bulging and general loss of tolerance.

Slippage of post-tensioning wedges — This has occurred occasionally with some systems. It has been readily rectified by using different wedges and/or changing the post-tensioning jacks.

Detailing — Many difficulties have arisen from inadequate allowances for reinforcing bar sizes, bending and placement of tolerances, conflicts between reinforcing bars and post-tensioning ducts, and so on. These come from many sources relating to basic design detailing, shop drawing preparation, reviews, and general coordination or lack thereof.

As a general observation, many of the above-mentioned problems have also been encountered in other types of construction. Examples include honeycombing, misaligned and blocked post-tensioning ducts, miscellaneous cracking, excessive camber growth, post-tensioning wedge slippage, inadequate tolerances, sweep and warp in girders, etc.

These and similar problems are a fact of life in all types of construction and will continue to be dealt with as a matter of routine. Experience shows that a "problem" becomes much more severe if individuals and organizations are not adequately prepared and experienced to resolve the particular problem as soon as it arises.

By their nature, segmental bridges involve the use of precast concrete and post-tensioning operations. Consequently, problems like those described here can be anticipated and — by care and forethought — avoided.

9. TIME

The initial introduction of segmental construction with the span-by-span systems in the Florida Keys achieved some quite remarkable rates of progress and span erection. Reports were common of two, three and occasionally more spans being erected in one week using this method. The factory-style quality control of the precasting also paid off in the quality of the final riding surface.

Introduction of the cantilever type of structure brought some unfortunate time delays with some of the first projects constructed. These delays arose primarily out of problems due to workmanship, inadequate equipment and lack of at-

Fig. 18. Segmental cantilever bridges under construction at I75/I595 Phase 2 project. (Contractor: Harbert/Westbrook Joint Venture. Designer: Beiswenger, Hoch and Associates)

Fig. 19. I75/I595 Phase 2 project under construction.

Table 7. Construction time summary.

Bridge	Contract time	Comments
Long Key	128	Bridge on time*
Seven Mile	84	6 months ahead
Niles Channel	135	Bridge on time/ahead
Channel Five	100	On time
Ramp I	100	On time
Skyway Approaches	105	Approaches on time — Late on main spans
I75/I595-1	135	Late
Palmetto	117	Late
Airport	213	Late
US 441/I595	—	On time/ahead
I75/I595-2	—	2 months ahead at an interim deadline — 9 months ahead at completion

*Approach area was casting yard for Long Key, Niles Channel and Channel Five Bridges.

tention to detail. Each problem caused some delay which spread over the whole construction period. Unfortunately, most problems could have been averted by proper care and attention. Mostly, they can be attributed to inexperience.

This situation changed significantly for the better with the latest projects nearing completion on the I595; namely, US 441/I595 and I75/I595 Phase 2 (Figs. 18 and 19). In both cases, an experienced contractor used well-trained crews under proper supervision. The design and shop drawing reviews were also done under experienced groups.

The net result was a considerable improvement in all respects. There were very few problems of the sort which troubled previous cantilever segmental projects.

A summary of construction times and comments is presented in Table 7. In general, projects ran better with experienced contractors and supervision groups.

Shop drawing preparation and reviews influenced time on some segmental projects. Improvements have been made in the whole process for more recent projects. Consideration is being given to future changes aimed at simplifying and reducing much repeated effort, especially for individual segment drawings.

10. COSTS

Contract dates and total project and bridge bid costs are shown in Table 8. A detailed breakdown of average unit costs and square foot prices, corrected for inflation to 1987, are given in Table 9. For the data available and within the vagaries of inflation, segmental bridges average \$44 to \$52 per sq ft (\$474 to \$560 per sq m) at 1987 prices.

It is interesting that on two recent interchange projects, which included bridge alternates in segmental concrete and steel, namely the I95/I595 Interchange and South Fork New River projects, the segmental bridges were lower in price than the steel. These projects were large and bridge construction amounted to only one-third of each total

Table 8. Project bids.

Bridge	Construction	Total project $million	Segmental portion $million
Built			
Long Key	1/79 - 7/81	15.1	14.5
Seven Mile	10/79 - 7/82	43.4	43.0
Niles Channel	4/81 - 4/83	7.9	7.7
Channel Five	5/81 - 1/83	10.4	9.0
Ramp I	2/82 - 5/84	22.3	4.6
Skyway Approaches	4/83 - 10/87	71.1	
I75/I595-1	7/83 - 11/87	10.2	8.8
Palmetto	3/84 - 9/86	9.4	7.8
Airport	10/84 - 12/87	7.8	5.3
US 441/I595	10/86 -	60.2	11.9
I75/I595-2	4/87 -	51.1	27.1
Not built			
I95/I595-DEF	6/87 -	(104)	31.2*
South Fork New River	6/87 -	(60)	19.8*
Howard Frankland	8/87 -	(44.9)†	(46.5)

*Segmental prices of next low bid given. Total project low bid included for building steel alternate at 8 percent higher than segmental.

†Bulb tee was low bid by 3.5 percent.

Table 9. Cost breakdown.

Bridge	Surface area sq ft (1000s)	Cost $ per sq ft (1987)
Long Key	468	38
Seven Mile	1376	34
Niles Channel	176	50
Channel Five	190	55
Ramp I	91	61
Skyway Approaches	416	—
I75/I595-1	252	4148
Palmetto	198	48
Airport	125	68
US 441/I595	177	50
I75/I595-2	537	56
I95/I595-DEF	561	
South Fork		46
New River	433	44
Howard Frankland	1060	

1987 Prices

Span-by-span avg $44 per sq ft

Cantilever avg $52 per sq ft

Substructure concrete $254 per cu yd

Superstructure segments $456 per cu yd

Post-tensioning $1.16 per lb

Reinforcing bars $0.42 per lb

Metric (SI) conversion factors:
10.76 sq ft = 1 m^2;
1 cu yd = 0.765 m^3; 1 lb = 0.454 kg.

Table 10. Average bridge costs in Florida.*

Types of bridges	Percentage of all bridge construction	$ per sq ft
Standard AASHTO girder overpass four spans with pier caps and columns	25	45 (484)†
AASHTO girder simple span trestle bridge with pile bents	40	29 (312)
Major structures of all types, large spans, long bridges, simply supported or continuous in steel or concrete including segmental	25	42 (452)
Other miscellaneous bridges, bascules, etc.	10	—
Overall average		36.4 (392)

*Based upon square footage of bridge type constructed.
†Figures in parentheses are in $ per sq m.

project. The bridges were built in steel because of the influence on the total bid of the remaining two-thirds of each project, which involved considerable roadway, retaining wall, embankment and complex utility work, etc. Incidentally, the traffic and construction plan for the steel alternate of the I95/I595 project has largely been worked to that devised for the segmental alternate.

All costs presented here are based on bid prices. There have been exceptional circumstances on a few projects, where additional costs have been incurred for correcting problems above and beyond the routine normally encountered with segmental or post-tensioned concrete construction. These relate to questions of detail, corrosion protection and materials, and to general design, construction and specification issues. They do not relate to segmental construction as a method for designing and building bridges.

On this basis, it is fair to compare costs with other types of construction and to note that on recent projects, segmental construction has been very competitive and most successful.

For comparison purposes, costs from a recent survey of 75 bridges built over 3 years up to fiscal year 1986-87 are summarized in Table 10. The averages in this table have not been corrected for inflation to 1987, so may be a few percent low. Nevertheless, it is clear that segmental bridges are competitive considering they are generally used for longer, more costly, spans and particularly on curved viaducts.

11. ADMINISTRATION PROCESSES — DESIGN, CONSTRUCTION AND SHOP DRAWINGS

The following section discusses some of the problems encountered within the segmental industry as a whole and offers recommendations for future improvements. It is based upon the author's experience on many segmental projects over the last 12 years and represents his own views which are not necessarily those of the Florida Department of Transportation, its agents, or any other organization. These ideas and proposals are intended to promote discussion, thereby leading to a better understanding and general improvement in this area.

11.1 Current Practice

The practice to date has been for contract documents to require and for contractors to produce many (often hundreds) shop drawings detailing each and every precast segment. The production, submittal, review and correction of shop drawings is an awesome burden for the contractor, designer and client. It invariably leads to delays, differences of opinion, professional posturing and claims. All this is quite unnecessary and serves no good purpose. The time has come to overhaul the shop drawing process as it relates to precast segmental bridges. But this involves more than shop drawings. It is necessary to start at the very beginning, clearly establishing:

1. The functions, roles and responsibilities of the Client, Designer, Construction Engineering and Inspection Agency, Contractor and Contractor's Engineer.
2. The limits of professional liability attached to the engineering aspects of each function and party.
3. The scopes of services to be provided by the Designer during design, shop drawing review and construction.
4. The scopes of services to be provided by Construction Engineering Inspectors during construction (especially "Engineering" functions).
5. The contractual and engineering obligations of the Contractor and his Engineer.
6. The communication and administration process, especially identifying routes for paper flow and responsible decision makers.
7. The function, responsibility and jurisdiction of the DOT and FHWA and their agents.
8. The complete integration and mutual agreement of design scopes, design guidelines and criteria, specifications and any special provisions attached to the contract.

Most, if not all, of these exist and are in force at this time both in Florida and other states. Difficulties have been experienced in the past when there have been ambiguities and differences.

11.2 Recommendations for Improvement

The author believes that a major improvement would be possible in precast segmental work by adopting some or all of the following:

11.2.1 Design Plans

1. Organize the plans for the convenience of the Contractor who has to fabricate and erect components.
2. Show details in full, either on or next to the sheet showing the component, and to a large scale.
3. Ensure that all reinforcing bar cages can be assembled easily

from simple bar shapes, avoiding as much as possible closed loops and multiple bends.

4. Ensure that reinforcing bar bending diagrams are shown in full in the plans adjacent to the component to which they apply or on the next sheet(s).
5. Ensure that reinforcing bar lengths and bends are according to normally accepted industry practice, amply allowing for bending tolerances.
6. Ensure that the reinforcing bars will fit inside the concrete dimensions, recognizing that there are construction tolerances (in the specifications) on concrete thickness and covers. Do not forget that a ribbed reinforcing bar is physically larger than its nominal diameter.
7. Completely dimension post-tensioning duct alignments through each segment. This is best done by quoting offsets vertically and laterally from known control lines or surfaces at regular intervals of no more than 2 to 3 ft (0.61 to 0.91 m) where small radii and reverse curves occur.
8. In anchorage zones, allow for the largest commercially available anchorage likely to be used with the tendons concerned. Then, if the Contractor elects to use a smaller anchorage, it can easily be accommodated with only a minor change to the very localized detail.
9. Ensure that all reinforcing bars are bent to avoid post-tensioning ducts. This implies an assumption about the size of duct likely to be used. In today's practice, most post-tensioning systems use ducts of similar size according to the number and size of strands in the tendon.
10. Clearly state on the plans that, in the event of a conflict between the post-tensioning duct and reinforcing bar, the post-tensioning duct alignment must take precedence and that the reinforcing bar shall be repositioned or replaced according to the direction of the Engineer.
11. Show the erection sequence that was assumed in the design, especially the sequences in which closures are made. Show where and at what stage of construction temporary supports or heavy equipment are placed on or removed from the structure.
12. Specify a sequence for post-tensioning.
13. Show the assumed ages of segments at the time of erection and all material properties assumed in the design.
14. Provide *deflections* at time of "infinity" and at the time of erection of the segments according to the assumed erection sequence, supports, equipment and times. Also, quote acceptable timing and load variations.
15. Quote assumed stiffness of temporary supports and erection equipment loads.
16. Provide an envelope of stresses for the top and bottom fibers resulting from all loads.
17. Quote the maximum loads, moments and shears in both directions that can be safely taken by substructure piers and foundations.
18. Quote all required loads, movements and settings for bearings and expansion joints.
19. Ensure that the drawings agree with the Contract specifications.

The emphasis in these should be upon constructibility for the convenience and benefit of the Contractor and Client. It should be apparent that, if they are properly included in the design plans, then the need for shop drawings repeating and redetailing much of this information is greatly reduced. Ideally, it should be possible to build a structure from the design plans with the exception of only a few items (as listed in the next section). In practice, there will always be a need for some flexibility in construction techniques which require minor adjustments to the design details.

It is the author's view that these procedures place little additional work upon the Designer. It is more a case of asking the Designer to organize his plans and produce details which comply with normal industry construction practice. In effect, this is also asking detailers (and for that matter, design engineers) to pay attention to practical detailing! It might require a little more effort in the future than in the past, but it will avoid the need for the Contractor to duplicate and then carry to completion that which was previously produced in large part by the Designer.

11.2.2 Shop Drawings

Given the above re-emphasis on constructible design plans, shop drawings should now be required only for:

1. Minor changes to details at anchorages to accommodate the Contractor's elected post-tensioning system.
2. Details of the post-tensioning hardware components themselves (manufacturer's standard drawings).
3. Details covering inserts or lifting holes.
4. Details covering localized strengthening for supports or special equipment placed in locations not already allowed for in the design plans.
5. Calculations pertaining to any localized strengthening for same. Major redistribution of supports or significant changes to erection equipment loads would constitute a need for at least global reanalysis of the structure by the Contractor and checking by the Engineer).
6. Checks and details for special handling, storage or stacking of segments.
7. Drawings and calculations prepared under the seal of a registered professional (structural) engineer for temporary falsework, special erection equipment, closure devices or other items needed for construction according to the Contractor's methods, with the exception of regular construction equipment such as commercially available cranes.
8. Casting cells and similar equipment.
9. Geometry control method in a handbook or manual format.
10. An erection control manual quoting the sequence of operations in great detail for the erection of each segment, stressing of each temporary and permanent tendon, movement of equipment and introduction or removal of supports and devices, etc. This manual is drawn up for the benefit of the field erection and construction supervision personnel and should be reviewed and approved by the Engineer for compliance with the intent of the design.
11. Casting curves. Only if the casting and erection operations differ significantly (the Designer should quote some allowable time and load variations in the plans) from the design should the Contractor be required to reanalyze the structure according to his own sequences, methods and timings in order to devise his own values of deflections. In all other cases, the casting curves should be produced from the deflections quoted on the plans. The Contractor should include his casting curves in or with his geometry control manual.

11.2.3 Comments

The above suggestions for improvements to "administration processes" would require the mutual cooperation of all sides of the industry: clients, states, the Federal Highway Administration, consultants, contractors, etc., and would probably be best pursued through the auspices of recognized professional and industrial organizations.

The Florida Department of Transportation has found benefits to other areas of operations and to other types of structures, not just segmental, through pursuing these kinds of improvements.

12. ACTIONS BY THE FLORIDA DEPARTMENT OF TRANSPORTATION

Since the introduction of the first segmental bridges, the FDOT has gained considerable experience and has taken many positive steps toward improving its own operations and this field. For example, it has:

1. Issued a "Design Criteria for Segmental Bridges" (1983/4) which has since been incorporated in the Department's Structures "Design Guidelines." (Parts of the original criteria have also been incorporated in the Post-Tensioning Institute's report of February 1988 entitled "Design and Construction Specifications for Segmental Concrete Bridges," prepared for the National Cooperative Highway Research Program.)
2. Clarified and improved specifications (Special Provisions).
3. Introduced "Designer Services During Construction" on all major bridge projects, regardless of type, in order to have immediate assistance available on any design related issues which may arise during the course of the project in addition to the needs of normal shop drawing reviews.
4. Tightened qualifications required of the Designer, the Construction Engineering and Inspection Agency and the Contractor.
5. Published a "Guide to the Construction of Segmental Bridges" (1987) for use by construction engineering and inspection personnel. An improved version is being prepared which separates the guide into "segmental" and "post-tensioning" manuals, the latter covering all types of post-tensioning construction.
6. Gained "hands-on" training for FDOT field engineers and inspection staff.
7. Prepared a "Structures Detailing Manual" for all bridge types.
8. Developed a "generic" segmental specification (unfinished).
9. Introduced a generic technical scope of services for "construction engineering and inspection" for all types of structures.
10. Written a three-dimensional geometry control desktop computer program for the casting control of precast segmental bridges. (This is based upon the author's own work originally undertaken for checking the geometry control of the Linn Cove Viaduct.)
11. Also, the Department's own design and construction consultants have gained experience.

Many of these items were also of benefit in other areas, for example, in post-tensioned structures of all types and administrative procedures.

Fig. 20. The Sunshine Skyway Bridge at night — a bright future for segmental bridges. (Courtesy of Figg and Muller Engineers Inc.)

13. BENEFITS OF SEGMENTAL BRIDGES

Much of the foregoing has concentrated on the problems and areas in need of improvement, overlooking the benefits of segmental construction.

The benefits include:

1. Precast production off site under factory-controlled conditions.
2. Concurrent production on and off site, i.e., substructure and foundation construction proceeds concurrently with segment manufacturing.
3. Rapid erection systems.
4. Overhead construction; may avoid obstacles, which is particularly valuable in congested urban areas and sensitive environments.
5. Preserves the environment.
6. Avoids extensive falsework.
7. Requires minimal onsite formwork and cast-in-place work.
8. Affords great flexibility in construction operations. This is valuable for maintenance of traffic on large urban interchanges and other congested areas.
9. Bridge construction is placed off the critical path.
10. Competitive concrete construction (especially in Florida).
11. Efficient for large span concrete structures.
12. The traditional segmental box is torsionally rigid which makes it ideal for curved bridges.
13. Substructures require less space than "conventional" beam construction, especially with high skew crossings. This offers great advantages in restricted locations.
14. Aesthetically attractive.

For more detailed information on the design and construction of segmental bridges, the reader should refer to specialist literature.[7,9,10]

14. SUMMARY

Over the last 10 years, Florida has been a leading state in the design and construction of precast segmental bridges. With the exception of the main span portion of the New Sunshine Skyway cable stayed bridge (Fig. 20), these precast segmental bridges mostly fall into two groups: either straight span-by-span over water or curved balanced cantilever viaducts at major interchanges. The spans involved generally range from 100 ft (30 m) to well over 200 ft (60 m), covering the intermediate span range beyond the limits of normal precast girder construction.

Span-by-span structures have not yet exceeded 143 ft (43.6 m). Recently, the new bulb tee was successful against the span-by-span segmental alternate for the Howard Frankland Bridge by a margin of about 3 percent. This initial result indicates competition in the shorter span ranges. However, in excess of this span length and on curved viaducts, segmental cantilever and steel are likely to remain more effective. Balanced cantilever bridges have been successful in interchange applications, especially because they can readily accommodate the varying alignments and span lengths typical of such locations.

Substructures are typically lighter by half for span-by-span compared to balanced cantilever structures. This is because of the basic difference in construction methods; most span-by-span structures have been founded on drilled shafts, whereas most cantilever structures are founded on driven piles. This reflects design philosophies as much as construction methods and geological conditions. It should be noted that span-by-span construction affords more opportunity to standardize pier shafts and so develop very efficient systems. In cantilever construction, piers tend to vary more in height and construction load requirements and each pier tends to be unique.

Contractors elected to use single cell casting machines, and most preferred to establish their own precast yards. All casting operations went through a period of mobilization, usually 3 to 4 months, followed by several weeks of learning before production reached a sustained rate of one segment per cell per day. Most operations achieved this rate. Casting operations were geared to the size and duration of the project, most being a completely new operation writing off the cost of the forms and yard on the job. Generally, robust equipment and forms saved time and money despite the higher initial outlay.

Erection operations for span-by-span bridges were either by truss or gantry. Balanced cantilevers were generally erected by cranes standing on the ground. All projects experienced a learning period of a few weeks or spans before achieving a sustained erection rate. Typically, span-by-span construction proceeded at three spans per week and balanced cantilever at four segments per day per cantilever. Higher rates were achieved occasionally.

Problems in segmental construction generally center upon attention to detail and quality of workmanship. The most significant factor, perhaps, is the ability to readily assemble the reinforcing bar cage and post-tensioning ducts without conflicts or misplacements and then ensuring that all the reinforcement in the ducts and other embedments remain in place during concreting. Misplaced and blocked post-tensioning ducts prevent successful construction. Attention to good workmanship and inspection pays dividends. Special care is needed in concrete placement, consolidation and finishing to ensure a good quality segment.

Successful erection depends almost entirely upon the quality of the segments. These problems are not just peculiar to segmental bridges; they have also occurred in other precast, post-tensioned AASHTO and bulb tee beam construction. As experience grows within the industry and the profession, such problems are less frequent. However, there is a need to educate and inform designers and detailers about practical constructible details and to enforce good workmanship through education and specifications.

There is also a need to address (nationwide) administration processes related to design, shop drawings, inspection and construction practices since much wasted effort has been involved. The author considers that much improvement is possible by the adoption of appropriate standards and practices. Such measures will make the entire administrative process more efficient.

15. CONCLUSIONS

Experience in Florida has shown that it is possible to complete segmental structures on time and ahead of schedule. Of the 11 major projects containing 31 bridges so far constructed, eight projects went well in casting and erection, and three others were delayed for a variety of reasons, mostly connected with inexperience. The latest projects are proceeding very well and will be completed ahead of schedule.

Segmental construction has successfully demonstrated its competitiveness in Florida against other alternates. For the span ranges and applications involved, it is likely to remain competitive for the foreseeable future.

While it is always possible to make improvements, Florida's experiences and successes clearly demonstrate that the learning and development phase has passed and that segmental technology has a place in the future of bridge engineering.

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* * *

NOTE: Discussion of this article is invited. Please submit your comments to PCI Headquarters by February 1, 1990.

APPENDIX

A more detailed breakdown of the information summarized in Tables 1 through 9 is provided in Tables A1 through A9.

Table A1. Precast segmental projects.

Project	No. of bridges	Bridge type		Bridge over		Geometry		Substructure		Driven piles	Drilled shafts	Spread footings
		Canti-lever	Span-by-span	Land	Water	Curved	Straight	CIP	Precast			
Built												
Long Key	1		•		•		•		•		•	
Seven Mile	1		•		•		•	•	•		•	
Niles Channel	1		•		•		•	•			•	
Channel Five	1		•		•		•		•		•	
Ramp I	1	•		•		•		•		•		•
Skyway Approaches	1		•		•		•		•	•		
I75/I595 Phase 1	5	•		•		•		•		•		•
Palmetto	5	•		•		•		•		•		
Airport	4	•		•		•		•		•		
US 441/I595 (M)	2	•		•		•		•		•		
I75/I595 Phase 2 (u)	9	•		•		•		•		•		•
Total	31											
Bid but not built												
I95/I595 (DEF)	8	•		•		•		•		•		•
South Fork New River	2	•		•	•		•	•		•		•
Howard Frankland	1	•	•		•		•	•	•	•		
Total	11											
In Design												
Port of Miami	1	•			•		•	•		•		
Edison	1		•		•		•	•	•	•		
Golden Glades	(N)	•		•		•		•		•		•

Table A2. Superstructure parametrics.

Project	Spans (ft)		Depth (ft-in.)	Bridge plan area (ft^2)	No. of bridges	No. of segments	Segment weights (tons)			ESCT* ft^3/ft^2	Reinforcing bar lb/ft^2	Transverse post-tensioning lb/ft^2	Longitudinal post-tensioning lb/ft^2	Structure type	
	Range	Avg					Typical	Pier	Abutment					Cantilever	Span-by-span
Long Key		118	7-0	468,358	1	734	66	62	49	1.34	4.48	0.63	1.50		•
Seven Mile		135	7-0	1,376,257	1	2154	65	68	52	1.35	6.85	0	2.21		•
Niles Channel		118	7-0	175,634	1	276	66	66	49	1.35	4.83	0.63	1.70		•
Channel Five		135	7-0	190,126	1	299	65	68	52	1.35	(6.85)	(0.63)	(2.21)		•
Ramp I	120-224	194	9-4	91,271	1	201	58	94	52/67	1.75	8.58	0.90	4.76	•	
Skyway Approach		135	8-0	415,530	1	584	75	83	34/40	1.42	6.66	0.50	1.87		•
I75/I595 Phase 1	100-200	160	7-3	251,680	5	567	52	70	38/61	1.61	8.36	0.97	3.82	•	
Palmetto	84-215	155	8-0	197,724	5	658	38	48	25/35	1.66	8.93	0.87	3.83	•	
Airport	85-162	121	7-3	124,520	4	286	54	70	62	1.68	11.06	1.07	3.63	•	
US 441/I595 (M)	124-224	159	8-3	177,199	2	385	56	98	71	1.71	14.50	1.10	3.59	•	
I75/ Single box	85-206	157	7-3	342,471	4	750	52	65	57/72	1.56	14.00	0.86	5.50	•	
I595 (2) Twin boxes	60-183	118	6-6	194,472	5	616	40	46	39	1.86	18.00	0.56	5.45	•	
I95/ Single box	71-205	161	6-6/ 8-3	420,606	7	896	56	90	61	1.63	—	0.82	5.27	•	
I595 Twin boxes	83-140	120	6-6	140,608	1	258	40	54	39	2.04	—	0.62	5.09	•	
South Fork New River	95-300	—	8-3/ 16-6	433,249	2	984	50/88	69/ 117	54/88	1.77	—	0.72	5.66	•	
Howard Approach	—	143	8-0	839,982	1	1584	70	43	40	1.61	9.43	0.80	2.69		•
Frankland Main Spans	143-231	—	11-0	219,540		544	55	48	45/54	1.79	8.40	0.77	3.67	•	
Port of Miami	96-195	—	9-3	268,906	1	496	75	100	95	1.89	—	0.84	—	•	
Edison	—	143	8-0	593,040	1	1242	64	40	—	1.59	7.79	0.73	2.83		•
Golden Glades	(100-225)		—	—	(N)	—	—	—	—	—	—	—	—	•	

*Equivalent solid concrete thickness of superstructure.
Metric (SI) conversion factors: 3.28 ft = 1 m; 1 ton (U.S.) = 0.91 tonne; 1 psf = 4.89 kg/m^2.

Table A3. Substructure parametrics.

Project	Spans (ft)		Height (ft)		Plan area (ft^2)	Substructure concrete (yd^3)	SCS*/VSB (per cent)	Reinforcing bars in substructure		Post-tensioning in substructure (lb/yd^3)	Bridge type		Substructure type	
	Range	Avg	Range	Avg (±)				Total lb	lb/yd^3		Cantilever	Span-by-span	CIP	Precast
Long Key		118		25	468,358	3,011	0.69	499,000	166	0		●		●
Seven Mile Main Spans		135	20-70	50	(145,000)	(3,400)	1.27	(410,000)	121	10		●		●
Seven Mile Approach		135		20	1,231,000	(4,400)	0.63	—	—	0		●	●	
Niles Channel		118	20-40	25	175,635	1,030	1.27	—	—	0		●	●	
Channel Five		135	20-70	50	190,126	(3,400)	0.57	(410,000)	121	10		●		●
Ramp I	120-224	194	35-49	42	91,271	2,561	1.80	396,620	155	0	●		●	
Skyway Approach		135	45-152	98	415,530	17,993	1.18	2,357,056	131	24		●		
I75/I595 Phase 1	100-200	160	28-60	42	251,680	8,036	2.05	1,182,591	147	0	●		●	
Palmetto	84-215	155	30-51	41	197,724	4,844	1.61	816,480	168	0	●		●	
Airport	85-162	121	24-40	32	124,520	3,524	2.39	570,538	162	0	●		●	
US 441/I595 (M)	124-224	159	25-81	54	177,199	7,312	2.06	1,060,184	145	0	●		●	
I75/I595 (2) Single box	85-206	157	30-97	59	342,471	15,636	2.09	2,411,683	157	0	●		●	
I75/I595 (2) Twin boxes	60-183	118		33	194,272	5,152	2.17	755,816	147	0	●		●	
I95/I595 Single box	71-205	161	—	(47)	420,606	15,200	1.96	No data			●		●	
I95/I595 Twin boxes	83-140	120	—		140,608	3,946					●		●	
South Fork New River	95-300	—	—	(63)	433,249	12,184	1.24				●		●	
Howard Frankland Approach	143	143	—	—	839,982	4,718	—					●	●	●
Howard Frankland Main Spans	143-231	—	—	—	219,540	6,054	—				●	●	●	●
Port of Miami	96-195	—	—	—	268,906	—	—	No data			●		●	
Edison	—	143	—	—	593,040	(3,000)	—					●	●	●
Golden Glades	(100-200)	—	—	—	—	—	—				●		●	

*Ratio of solid concrete in substructure to void spanned by the bridge.
Metric (SI) conversion factors: 3.28 ft = 1 m; 1 lb/yd^3 = 0.59 kg/m^3.

Table A4. Casting operations.

Project	Superstructure Numbers and types of segments				No. of casting cells			Learning period/ phase		Sustained production rate after learning phase		
	Typical	Pier	Abutment/ Other	Total	Typical	Pier	Abutment/ Other	Appox. Weeks	No. of segments	Typicals per week	Others per week	Total per week
Long Key	618	90	26	734	3	1	—	—	—	15	2	17
Seven Mile	1850	228	76	2154	5	—	1	—	—	25	2-3	28
Niles Channel	232	34	10	276	3	1	—	—	—	15	2	17
Channel Five				288	3	1	—	—	—	15	2	17
Ramp I	187	10	4	201	(1)	1	—	—	—	—	—	—
Skyway Approach	504	64	16	584	2	1	2		10			10
Skyway Main Spans	319	14	—	333	2	1	2					5
I75/I595 Phase 1	187	10	4	567	2	1	1	20	18	5-10	2	10
Palmetto Single box	461	25	12	498	3	1	—	20	19	15-25	4	(24)
Twin boxes	144	8	8	160	2	1	—					
Airport	258	20	8	286	2	1	—	4-6		10	2	12
US 441/I595 (M)	356	25	4	385	2	1	—	4-6	4-6	10	1	11
I75/ Single box	689	47	14	750	4	1	1	3-5	15	—	—	29-35
I595 (2) Twin boxes	550	46	20	616	3	1	—					(>50 max)

Notes:

1. Learning phase is approximate estimate after mobilization.
2. Sustained weekly production rates are averages.
3. All segments for Niles Channel and Channel Five were made at Long Key using same equipment.
4. Precast substructure segments are not included.

Table A5. Rejected segments.

Project	Superstructure segments lost and reasons	Attrition — segments lost/total	Loss (percent)
Long Key	2 — Voids/honeycombing 2 — Accident	4/734	0.5
Seven Mile	2 — Voids/honeycombing 1 — Improper stacking	3/2154	0.2
Niles Channel	0	0	0
Channel Five	1 — Voids/honeycombing (cement/material problem)	1/299	0.4
Ramp I	1 — Accident	1/201	0.5
Skyway Approach	1 — Damaged shear keys 1 — Hurricane damage 1 — Other	3/584	0.5
Skyway Main Spans	1 — Collapse of gantry	1/333	0.3
I75/I595 Phase 1	18 — Various reasons — Voids/honeycombing/displaced post-tensioning ducts	18/567	3.2
Palmetto	19 — Various reasons — Voids/honeycombing/displaced post-tensioning ducts out of tolerance concrete thickness/weak forms (4 or 5 had to be discarded when earlier segments were rejected)	19/658	2.9
Airport	0 — But poor riding surface finish	0	0
US 441/I595 (M)	1 — Accident	1/385	0.2
I75/I595 Phase 2	1 — Thermal shock 1 — Low strength 1 — Strands grouted before being stressed	3/1366	0.3

Table A6. Erection methods.

	Construction		Segment delivery			Erection equipment/supports				Erection time and completion		
Project	Canti-lever	Span-by-span	Low-boy	Barge	Crane	Stability towers	False-work	Truss/ Gantry	Beam and winch	Learning period	Sustained rate	Bridge completion
Long Key		•		•				•		3-4 weeks	3 spans/week	On time
Seven Mile		•		•				•		3-4 weeks	3 spans/week	6 months ahead
Niles Channel		•		•				•		None	3 spans/week	On time
Channel Five		•		•				•		None	3 spans/week	On time
Ramp I	•		•		•	•	•			—	—	On time
Skyway Approach		•		•				•		2 spans	2½ spans/week	On time
Main Spans	•		•		•			•	•	3 cycles	—	Late
I75/I595 Phase 1	•		•		•	•	•			Many weeks	10-15 seg/week	Late
Palmetto	•		•		•	•	•			A few weeks	15-25 seg/week	Late
Airport	•		•		•	•	•			Many weeks		Late
US 441/I595 (M)	•		•		•	•	•			4-6 weeks	> 10 seg/week	Ahead
I75/I595 Phase 2	•		•		•	•	•		•	2-3 weeks	> 30 seg/week	9 months ahead

Table A7. Construction time summary.

Project	Original calendar days	Extended calendar days	Final calendar days	Time used percent	Comments
Long Key	915	1054	1352	128	Long Key completed on time, approach was casting yard for Niles and Channel Five
Seven Mile	—	—	—	<100	Completed 6 to 7 months ahead of schedule
Niles Channel	420	546	739	135	Structure completed ahead of schedule
Channel Five	—	—	—	<100	Structure completed on time
Ramp I	675	—	675	100	Structure completed on time
Skyway	900	1416	1480	105	Approaches went well, time lost on main span cable stays, etc.
I75/I595 Phase 1	920	1149	1539	134	Delayed due to structural problems, repaired ok
Palmetto	730	742	868	117	Delayed
Airport	490	585	1244	213	Delayed
US 441/I595 (M)	1300	1300	—	<100	Bridges on time or ahead
I75/I595 (U)	1052	1052	—	<100	60 days ahead at interim deadline, full completion approximately 9 months ahead of schedule
I95/I595 (DEF)					Steel alternate built } due to total project bid but segmental bridge prices were actually cheaper than steel
South Fork New River					Steel alternate built
Howard Frankland					Bulb tee alternate 3 percent lower than segmental

Table A8. Project bids.

Project	Start date	Actual finish date	Total project bid amount ($)	Segmental bridge portion ($) bid	Comments
Built					
Long Key	January 79	July 81	15,097,276	14,500,000±	
Seven Mile	October 79	July 82	43,394,764	43,000,000±	
Niles Channel	April 81	April 83	7,906,574	7,700,000±	
Channel Five	May 81	January 83	10,363,912	9,000,000±	
Ramp I	February 82	May 84	22,344,172	4,628,000	
Skyway Approach and Main Spans	April 83	October 87	71,132,079	71,132,079	
I75/I595 Phase 1	July 83	November 87	10,176,199	8,765,000	
Palmetto	March 84	September 86	9,445,663	7,825,000	
Airport	October 84	December 87	7,793,829	5,292,178	
US 441/I595 (M)	October 86	(July 89?)	60,243,919	11,938,000	Project ahead of schedule
I75/I595 Phase 2	April 87	(July 89?)	51,132,584	27,054,000	Project ahead of schedule
Not built					*Segmental price of second low bid
I95/I595 (DEF)	—	—	(104 million)	(31,193,000)*	Steel alternate built at $35,641,918†
South Fork New River	—	—	(60 million)	(19,753,000)*	Steel alternate built at $21,109,633
Howard Frankland	—	—	(44.5 million)	(46,500,000)	Bulb tee alternate built at $44,500,000
In design					
Port of Miami	(June 89)		$21 million estimate		†Steel bridge built since it was only part of the overall project bid which included roadway, ramps, walls, utilities, etc.
Edison	(Sept. 90)		$25 million estimate		
Golden Glades	(1990s)				

Table A9. Cost breakdown.

Project	Contract start date	Structure type		Segmental bridge bid ($ millions)	Plan area (ft², 1000 s)	$/ft² breakdown			$/ft² Adjusted to 1987	Unit prices adjusted to 1987			
		Cantilever	Span-by-span			Total $/ft²	Superstructure $/ft²	Substructure $/ft²		Substructure concrete $/yd³	Segments $/yd³	Post-tensioning $/lb	Reinforcing bar $/lb
Built													
Long Key	Jan 79		•	14.5	468.4	31.0	—	—	38				
Seven Mile	Oct 79		•	43.0	1376.3	31.2	—	—	34				
Niles Channel	Apr 81		•	7.7	175.6	43.9	—	—	50				
Channel Five	May 81		•	9.0	190.1	47.3	—	—	55				
Ramp I	Feb 82	•		4.63	91.3	50.7	40.7	10.0	61	206	577	1.55	0.44
Skyway Approach	Apr 83		•	—	415.5	—	—	—	—				
I75/I595 Phase 1	Jul 83	•		8.77	251.7	34.8	27.4	7.3	41	207	320	1.40	0.51
Palmetto	Mar 84	•		7.83	197.7	39.6	29.4	10.2	48	159	449	1.20	0.43
Airport	Oct 85	•		5.29	124.5	42.5	26.8	15.7	48	225	371	1.13	0.36
US 441/I595 (M)	Oct 86	•		11.94	177.2	67.4	48.0	19.4	68	334	636	1.00	0.40
I75/I595	Apr 87	•		27.05	536.7	50.4	36.9	13.5	50	300	409	1.00	0.34
Bid but not built													
I95/I595 (DEF)	Jun 87	•		31.19	561.2	55.6	37.9	17.7	56	350	428	0.85	0.45
South Fork New River	Jun 87	•		19.75	433.3	45.6	—	—	46	—			
Howard Frankland	Aug 87	•	•	46.50	1059.5	43.9	—	—	44	—			
In design													
Port of Miami	(1989)	•		(21)	268.9	—	—	—					
Edison	(1990)		•	(25)	593.0	—	—	—					
Golden Glades		•		—	—	—	—	—					
						Averages: Cantilever			52	254	456	1.16	0.42
						Span-by-span			44				