Segmental Design of The Harbour Island People Mover

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The Harbour Island People Mover is an elevated system (see Fig. 1) which links the mainland of downtown Tampa with Harbour Island, a billion dollar commercial development. The People Mover is actually an automated vehicle which transports pedestrians to and from the development. Visitors to the island can park in the multilevel garage at the mainland terminal (see Fig. 2) and conveniently ride this "horizontal elevator" to Harbour Island.

The $2.8 million contract for the project was awarded on a design/build fast-track basis to Misener Marine Construction, Inc. of Tampa. After establishing the shape and design parameters for the guideway structure, Misener subcontracted with LEAP Associates International, Inc. to design and produce the shop drawings for the precast prestressed portion of the project. The fabrication of the prestressed elements was subcontracted to Florida Prestressed Concrete and the vehicle operational system was designed and supplied by Otis Elevator Company, Transportation Technology Division.

The scope of work performed by LEAP was divided into two parts: a segmental portion and the balance of the

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Describes the design and construction features of
the precast prestressed segmental span of the
Harbour Island People Mover, part of a billion dollar
commercial development project in Tampa, Florida.

Fig. 1. Segmental span of the Harbour Island People Mover which links the mainland of downtown Tampa with Harbour Island, a billion dollar commercial development.

project. The two-piece segmental portion is the center span of a three-span continuous guideway which spans the Crosstown Expressway (see Fig. 3). The balance of the project, which actually constitutes the bulk of the project, consists of a guideway supported by single precast prestressed concrete box beams grouped into units made continuous for live loads.

The focus of this article is on the analysis and design of the precast segmental portion of the project. It was this part that proved to be the most interesting and challenging part with regard to LEAP's involvement in the project.

First, the basic layout of the entire system will be discussed including some of the reasons for selecting a segmental design. Then, the highlights of the analysis and design techniques will be discussed which include the loads considered, the analysis tools used, and the actual design methodology. Some unique aspects involved in the production of the precast prestressed components also will be described. Finally, a few of the special problems encountered during construction, to which interesting solutions were found, will be presented.

Structural System

The main structural system of the people mover consists of a concrete guideway composed of precast prestressed voided box beams supported by cast-in-place concrete piers founded on drilled shafts. A total of 34 spans were used which were grouped into 12 units of one, two, three, and four spans which are continuous for live load. The total length of the project is roughly 2500 ft (762 m).

The spans of the system are basically linear with the stationing running adjacent to and along the centerline of Franklin Street (see Fig. 3). Two groups of two cable-driven passenger cars traverse the system on cushions of air, each group traveling in the opposite direction with respect to the other.

Most of the guideway of the system is a single track. However, at the bypass region (see Fig. 3), where the cars pass each other enroute to their respective terminus points, there is a double lane. This region is characterized by a double box beam arrangement whereas the other areas have only one beam per span.

A section taken near midspan of the segmental span revealing the compo-

Fig. 2. The Fort Brooke parking garage is at the mainland terminus of the People Mover.

nent parts of the system is shown in Fig. 4. The four basic parts are the box beam, deck, flying surface, and rails. For purposes of comparison, a typical section through a nonsegmental part of the project is shown in Fig. 5. Note that the sidewalls of the segmental box were thickened to accommodate the post-tensioning ducts.

The 48 x 54 in. (1219 x 1372 mm) voided box beam has end regions which are solid for approximately 5 ft 7 in. (1.71 m) at each end. Two intermediate diaphragms, located at approximately third points, were used in each of the 70-ft (21.3 m) segments which make up the segmental span. The thicknesses of the end regions and the intermediate dia-
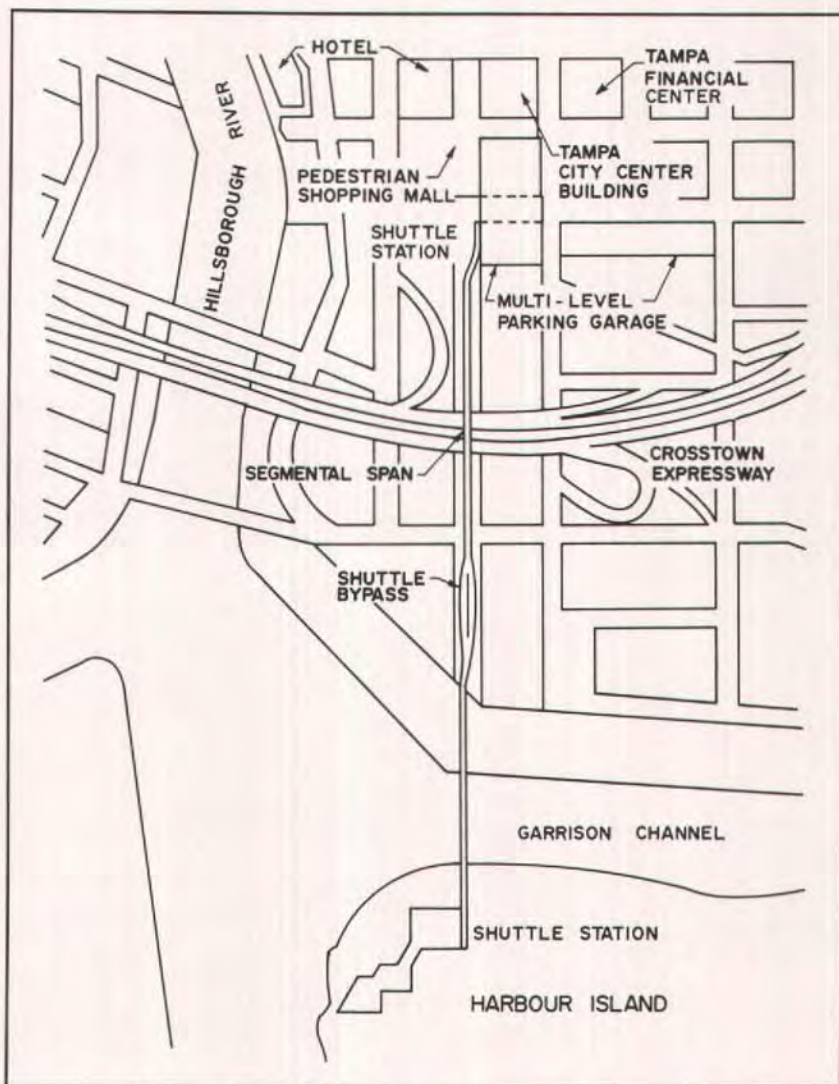

Fig. 3. Sketch showing major areas of the project and the locations of the main landmarks in the vicinity.
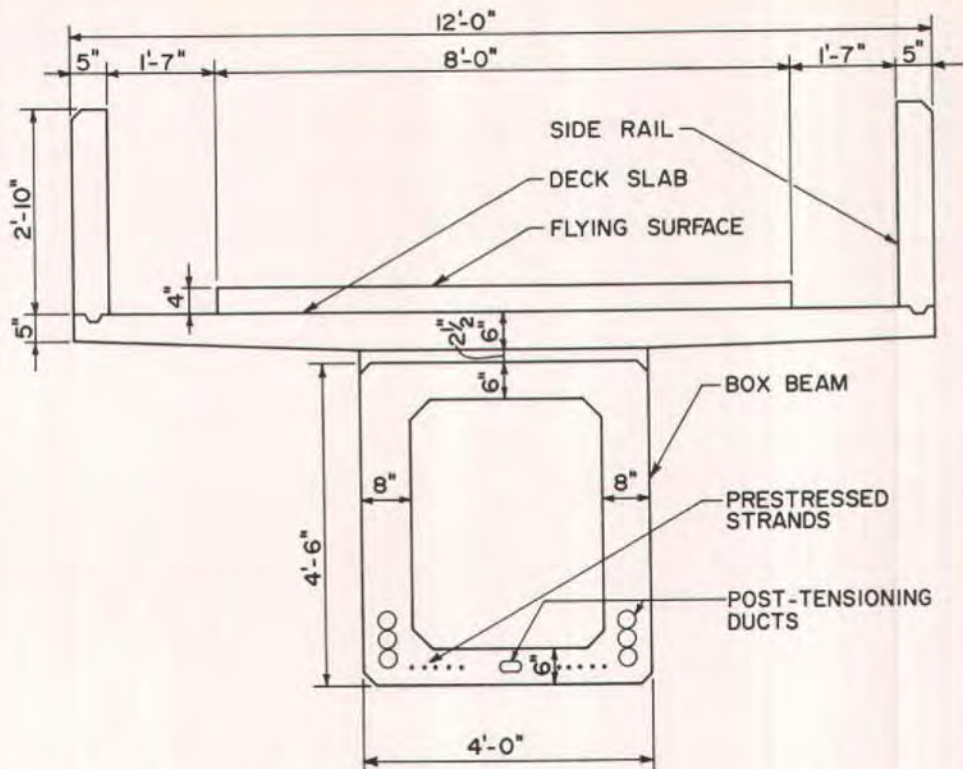
Fig. 4. Section through midspan of the segmental portion reveals the post-tensioning ducts and prestressed strands.

phragms were controlled by the shape and placement of styrofoam voids (see Fig. 6).

A 28-day concrete strength of 5000 psi (34.5 MPa) was required in the design of the boxes. However, cylinder tests showed strengths consistently well above this value throughout the project.

The deck is 6 in. (152 mm) thick directly above the box (plus a build-up of varying thickness) and tapers to about 5 in. (127 mm) at the outer edges. The nominal width of the deck is 12 ft (3.66 m) and is centered on the vertical axis through the centroid of the box. Small keyways were formed near the edges on the upper surface of the deck where the rails are joined. The deck as well as the other cast-in-place components were

designed with 5000 psi (34.5 MPa) concrete.

The rails, located at each extreme edge of the deck, have rectangular cross sections measuring 5 in. x 2 ft 10 in. (127 mm x 0.86 m). The flying surface measures 8 ft x 4 in. (2.44 m x 102 mm) and, as with the deck, is centered on the box beam.

Why Segmental Design?

Length was one of the main design constraints which affected the three options considered for the span over the Crosstown Expressway. The Expressway Authority prohibited the placement of a permanent bent between the roadways of the expressway. This meant that
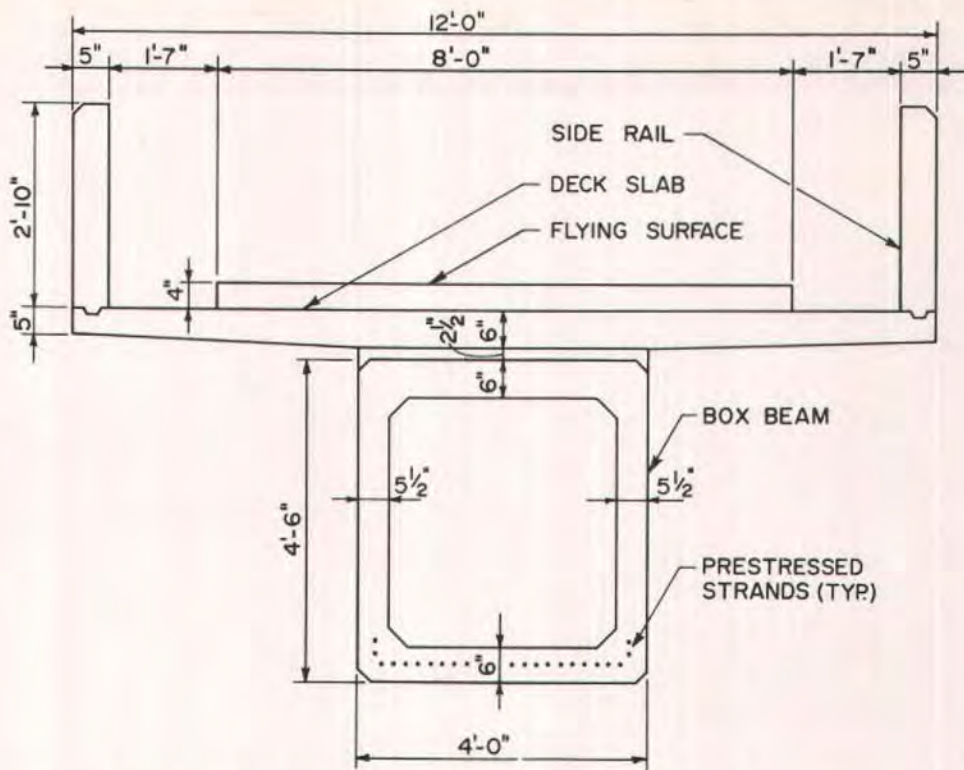
Fig. 5. Section through nonsegmental portion shows thinner side walls in these spans.

the span length had to be a minimum of about 140 ft (42.7 m).

The first of the possibilities considered was a steel box section. Designing a steel section to span 140 ft (42.7 m) would have been possible. However, since a high premium was placed on architectural impressions, this option was quickly ruled out since it would not have blended very well with the concrete sections used in the balance of the project.

Also considered was the same one-piece design used on the rest of the project. Parallel strand patterns were used in these cases, but this was not possible for this long of a span because a suitable strand pattern could not be found to satisfy both service conditions and ultimate strength requirements

without changing to a larger box cross section. Moreover, it would have been very difficult to transport and erect a single 140-ft (42.7 m) girder.

The solution adopted, which was suggested by LEAP, was to use a post-tensioned segmental design. Two 70-ft (21.3 m) segments could be easily handled and once erected on a temporary bent, could be post-tensioned together. By using bundled strands in ducts, a sufficient eccentricity at midspan could be achieved to satisfy design requirements. A box section with the same exterior dimensions as the other boxes could be used and so the architectural requirements were easily satisfied with this option. Additionally, the maintenance requirements would be lower than for steel.
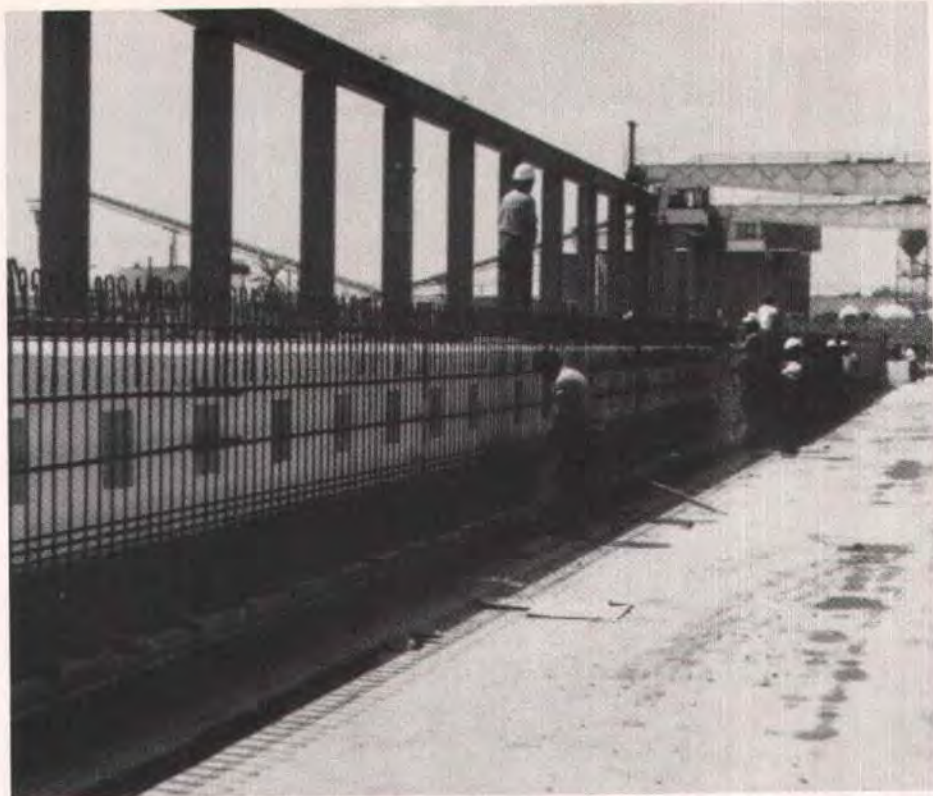
Fig. 6. Reinforcing scheme of a typical beam prior to the side forms being lifted into place.

Design Aspects

The loads acting on various parts of the overall system were grouped into five general categories: vehicle loads, dead loads, wind, thermal forces, and shrinkage and creep forces. These loads were combined into three critical load cases.

Case I consisted of the car, dead, shrinkage and creep, and thermal loads. Case II consisted of the same loads as Case I except that full wind load was substituted for the car load plus all loads were reduced by 25 percent. Case III consisted of car, dead, partial wind, shrinkage and creep, thermal, and braking loads which were also reduced by 25 percent.

As a consequence of the method and sequence of construction of the segmental span, there was actually one other component load which acted on the segmental unit. This was the load which was placed on the structure to simulate the removal of the shoring. A summary of the construction procedure which gave rise to this other load component follows.

The two segments were first erected on the permanent supports and the temporary bent and then post-tensioned together (see Figs. 7 and 8). This caused both pieces — now acting as one unit — to lift up off the temporary bent approximately ¼ in. (6.3 mm). The bent was then raised enough to come firmly into contact with the 140-ft (42.7 m) girder — the so-called touch shored condition.

Fig. 7. Traffic was detoured on the Crosstown Expressway while one of the two 70-ft (21.3 m) segments is being erected. Note the temporary bent at the left.

Fig. 8. Closeup view at the temporary support side of the other 70-ft (21.3 m) segment being set into place.

At that point, the deck and rails were sequentially cast. Since the temporary bent was snugly in place, all additional weight (the deck and rail weight) acting on the box beam had a two-fold effect: negative moments developed over the support and the reaction at the temporary bent increased with each increment of load added.

The resulting reaction at midspan was then viewed as simply an upward point load required to maintain zero net deflection. Consequently, if a load opposite in direction and equal in magnitude were superimposed at the points of reaction, the result would be zero. That is, the effect of the support would become zero. Therefore, the removal of the temporary support was modeled as a downward point load equal in magnitude to the reaction at the temporary support.

Role of Computers in the Design

Perhaps the single most useful tool in engineering analysis aside from the calculator is the computer. This proved to be especially true in the analysis and design of this project. The leveraging effect of the available manpower provided by the computer provided for an economical design that otherwise may not have been feasible, given the fast-track time constraints of the job.

Although numerous programs were used throughout the design, there were three major ones in particular that are noteworthy. The first is PM, a program which was written to simulate the movement and effects of the passenger cars as they traversed the system. The heart of PM is CON-BEAM, a continuous beam analysis program which LEAP previously developed.

The moment and shear envelopes generated by this program were input into the second program, BRIDGE, which is for the design of prestressed bridge girders. Finally, frame analyses which were performed by Misener Marine using McAuto's STRUDL were used to gain supplementary information for the design.

PM is essentially a routine which incrementally steps a uniform load of given length across a continuous beam while observing such things as the boundary conditions of the structure. The shuttle groups (each composed of two cars linked together) were designed to ride on a cushion of air and were therefore simply modeled as uniform loads 80 ft (24.4 m) in length.

As these loads moved from the end span to the segmental center span to the other end span of the three-span continuous unit, the maximum positive and negative moment envelopes and maximum shear envelopes were captured for each span. The maximum reactions at the piers, both positive and negative, were also saved.

The results from PM were then input directly into BRIDGE (which was the precursor to the SPAN program). For all spans except the segmental span, the main reinforcement was designed using BRIDGE. For the segmental span, however, BRIDGE was only used to design the prestressed reinforcement which supported only the handling and construction loads. The post-tensioned reinforcement, the main reinforcement for the segmental span, was manually designed for the moment and shear envelopes provided by PM.

Misener Marine performed comprehensive lateral load analyses for each of the continuous units which make up the People Mover using STRUDL. Separate analyses for braking and cornering forces induced by the cars and wind loads of 45 and 110 miles per hr (72 and 176 km/hr) were performed. Additionally, analyses for plus 30°F (17°C) and minus 40°F (−22°C) changes in temperature were performed.

The results of the thermal analysis obtained from the STRUDL output were used to calculate the forces and

moments caused by the shrinkage and creep of the concrete. The strains due to shrinkage and creep were calculated and, knowing the thermal properties of concrete (the concrete strains due to changes in temperature were easily calculated from these properties), a constant of proportionality was determined. This constant of proportionality was then used to estimate the forces and moments due to shrinkage and creep from the forces and moments induced by thermal strains.

Design of the Segmental Span

Once a design procedure was established and the necessary analyses were performed, the actual design of the segmental span was very straightforward. The design was divided into three main parts. First, the necessary reinforcement and connections to handle the vertical loads were designed. Next, lateral loads resulting from both wind and cornering of the cars were investigated. And finally, the torsion reinforcement was designed.

Each 70-ft (21.3 m) segment has a nominal number of ½-in. (12.7 mm) diameter low-relaxation strands in it to resist handling and construction loads. The strands were arranged in a parallel pattern with some of the strands debonded near the ends of the segments to control top tensile stresses near the ends resulting from the large eccentricity of the centroid of the strand group. By using this arrangement in place of a depressed strand pattern, a significant savings in time and expense in casting the girders was realized.

Whereas prestressed strand was only considered minor temporary reinforcement in the segmental span, it was the main flexural reinforcement in the other spans of the project. The same parallel/debonded strand patterns were used on those spans as well.

The design of the post-tensioned reinforcement for the segmental span, the main reinforcement for bending about the horizontal axis, was essentially divided into five main parts. The midspan stresses from all load components were first calculated and then summed. With this information, the required total final post-tensioning force and tendon profile were calculated such that there was zero tension at the bottom of the joint between the segments at final conditions.

The stresses immediately after post-tensioning were then checked against the allowable limits. Next, a complete stress history at final conditions was tabulated and again checked against the allowable limits. Lastly, the ultimate capacity was checked for structural adequacy.

Once the total required final post-tensioning force and parabolic tendon profile were established, the actual number of tendon ducts and numbers of strands in each duct had to be determined. This was done by Dywidag Systems International, the suppliers of the post-tensioning system for the project.

Three parabolic ducts in each side wall (see Fig. 9) and one straight duct in the bottom flange of the box beam were used. Within these seven ducts were placed a total of fifty-seven 0.600-in. (152 mm) diameter, low-relaxation strands. The post-tensioning strands were fully grouted within the corrugated galvanized steel ducts.

Lateral bending was actually of little consequence in the design of the box beams. The main reinforcement for lateral bending was longitudinal mild reinforcement located in the deck. Nevertheless, the possible adverse effects of lateral bending on the box beams themselves were investigated.

Torsional forces, on the other hand, required much more detailed consideration. These forces resulted from cornering loads of the cars and wind acting on both the structure and the cars. The

Fig. 9. End view of one of the segments. Note the three ducts and base plates in each side wall.

primary mechanism for the torsion was the differential bending of the piers which were of varying height.

Closed stirrups anchored in the deck were used as the reinforcement for shear and torsion. In calculating the contribution of stirrup area due to torsion, the voided box was taken as a solid section, as allowed by the provisions of the ACI 318-83 Code.

Production Aspects of Precast Segments

The precast concrete components were manufactured by Florida Prestressed Concrete at their plant in Tampa, about 10 miles (16 km) from the project site.

A high degree of precision was maintained in casting the members because the dimensional tolerances had to be exact for the segmental operation to proceed successfully.

An interesting production problem arose in that the void location of the precast sections had to be controlled within ¼ in. (6.3 mm). Production concepts investigated included casting the lower layer, then fixing the voids and casting the remainder, or fixing the voids vertically and horizontally to allow the concrete to flow across the 4 ft (1.2 m) dimension under the void.

The second method was chosen in conjunction with a high-range water-reducing agent (superplasticizer). A void holding apparatus was developed to ensure lateral location. Two vertical rods were secured at 4 ft (1.2 m) through the void and the form to the permanent hold-down locations under the form to prevent void floating.

Shipment of the precast components was on a truck trailer where a special bolster was mounted to the fifth wheel and a steerable dolly was used in the rear.

Fig. 10. Bearing failure cracks formed in some of the girders cast early in the project. The cause was quickly identified and a solution to the problem was found.

Special Problems and Solutions

Several rather interesting problems were encountered on this project. Although there were many small routine problems to which straightforward solutions were found, two in particular are noteworthy. The first was the effects of shrinkage and creep of the box beams and the second was a spalling problem at the bottom ends of some of the beams cast early in the project.

It was estimated early in the project that the magnitudes of the shrinkage and creep forces would be significant. The strains from shrinkage and creep were evaluated for each span, and then the corresponding forces and moments were determined by taking a proportion of the thermal forces and moments which were provided in the STRUDL analyses, as discussed earlier. For a continuous structure with high levels of prestress, the amount of reinforcement required to resist these forces can be and often is relatively large.

In this particular case, eight #6 bars were required in the ends of the boxes to resist the axial forces and positive bending moments at the piers (negative moments are resisted by mild steel reinforcement in the deck). Although not large in absolute terms, these bars were large enough to require special attention as to how to place them so that they could adequately develop within the very limited space available.

Fig. 10 shows several vertically inclined cracks at the extreme ends of the beams that appeared at release. Close examination of these cracks indicates that they are characteristically similar to bearing failure cracks. With this clue in mind, a probable mechanism for the cracking was determined. Release of the strands caused the member to camber up and simultaneously shorten elastically. The member was then supported only at its extreme ends.

As the member began to shorten, tensile forces developed in the bearing region which were caused by friction between the support points of the member and the casting bed. The shear capacity of the concrete was exceeded,

Fig. 11. Finished view of Harbour Island People Mover which is now fully operational.

and thus cracks formed.

While the effects of these cracks were very localized at the ends of the beams and, therefore, structurally insignificant once the beams were in place, it was, nevertheless, important that a solution be found because of the aesthetics involved. The remedy that was chosen was to create a chamfer strip transversely across the ends of the beams and for a short distance longitudinally along the span.

This solution effectively cured the bearing problem with minimal time and expense. The beams that did have minor cracks before the problem was identified were patched with a high strength grout that blended well with the original concrete.

Closing Comments

Construction of the structural system for the Harbour Island People Mover began in February 1984 and was completed last August. The complete system is today fully operational and open to the public (see Fig. 11).

The total design/construction cost of the elevated structure (excluding the mechanical system) was $2.8 million. Of this amount the precast prestressed portion represented about 20 percent.

The Harbour Island People Mover provides an outstanding example of one of the many uses of prestressed concrete. From its practicality as a construction medium to the strong architectural impressions it creates, the desirability of prestressed concrete is exemplified in many ways in this project. As one of the focal points of downtown Tampa, these attributes are certain to provide convincing and continuing proof of its use as a viable construction material.

Credits

Owner: Harbour Island, Inc., Tampa, Florida.

Designer/Contractor: Misener Marine Construction, Inc., Tampa, Florida.

Precast Engineer (Elevated Segmental Structure): LEAP Associates International, Inc., Tampa, Florida.

Precast Concrete Manufacturer: Florida Prestressed Concrete, Tampa, Florida.

Post-Tensioning Supplier: Dywidag Systems International, USA, Inc., Lincoln Park, New Jersey.