Metrorrey's Linea 2 Extension Viaduct in Monterrey, Mexico: A Revolution for Light Rail Concrete Segmental Bridges

Juan José Goñi Baamonde, Ph.D., P.E., Garcia Bridge Engineers, Tallahassee, FL
Antonio M. García y Benitez, P.E., Garcia Bridge Engineers, Tallahassee, FL

ABSTRACT

*Metrorrey's new 6.6 km. long Linea 2 Extension viaduct in Monterrey, Mexico, (currently under construction) includes a revolutionary concept for concrete segmental light rail bridges developed by the first author of this paper. The 37 m long 9.2 m wide typical spans have a "U" shape cross section that allows the two rail tracks to be placed within the structure envelope. This structural concept reduces noise, the danger of derailment and the visual impact. In addition, the typical segment only contains 76 lbs/cy of structural reinforcing (**using exclusively #3 bars**) whereas most current light rail segmental bridges contain, typically, about 200 lbs/cy. This is accomplished with a unique use of transverse and longitudinal internal tendons. The concept offers a viable and more economical alternative to the typical box girder cross sections for light rail bridges.*

Keywords: Transit, Light Rail, Metro, Segmental, Precast, Long Line, Span-by-Span, Monostrand, Greased-and-Sheathed, "U" Girder, "Omega" Girder,

INTRODUCTION

The metropolitan area of Monterrey, Nuevo Leon, is the third largest in Mexico with a total population of about 3.7 million inhabitants. It is located just 240 km (150 miles) south of Laredo Texas.

In 1992 Linea 1, the first line of the Metro of Monterrey (Metrorrey) with a total length of 18.5 km (11.6 miles), was completed and open to the public. The concrete segmental structure (Figure 1) was designed under the leadership of the late Jean Muller by Jean Muller International (Mondorf[1]) and built by CONSTRUMETRO, a consortium of three local firms: Tiasa (Protexa), Constructora Maiz Mier and Constructora Lobeira. The structure comprises typical simple spans about 27 m (89 ft) long with a maximum length of 36 m (118 ft). The box girder has a width of 7.40 m. (24.3 ft) and a depth of 2.13 m (7 ft.) .

Fig. 1 Metrorrey Linea 1 Concrete Segmental Viaduct

While this viaduct is an efficient system for transporting people, it has serious aesthetic deficiencies (See close up above): noticeable wavy segment joints, rust in columns and lack of uniformity in the color of the segments. These have prompted negative comments from the citizens and motivated Metrorrey to explore alternative concepts for extension of the Linea 2.

CONCEPTUAL DESIGN OF THE LINEA 2 EXTENSION

Metrorrey's Linea 2 was completed in November 1994 and comprises a cut-and-cover tunnel built under the city's congested downtown. To extend the line northward, Metrorrey's project managers decided that a viaduct (and a transition section from tunnel to viaduct) was the most economical system. To avoid a negative response from the citizens and merchants in the neighborhoods affected by the construction of the viaduct, Metrorrey's engineers evaluated other metro lines around the world and found that the cross section developed for the Santiago de Chile and Taiwan metros (Figure 2) could help to resolve the aesthetic deficiencies of the previous project. Avoiding negative input from those affected was critical for acquiring the necessary permits and capital to complete the project.

Fig. 2 Santiago de Chile Metro Viaduct

This cross section had been previously suggested by Leonhardt[2] for railway bridges (See Figure 3). Consequently, the Linea 2 extension design was tendered in 2003 with instructions to the designer to incorporate a cross section similar to the one used in Santiago de Chile. In addition, the distance between the top of the rails and the top of the top flange had to be such that the passengers could use the top flanges to exit the vehicle in case of derailment or other emergencies. Furthermore, to eliminate the aesthetic deficiencies associated with the noticeable segment shear keys (especially when they are broken) in Linea 1, the project managers preferred a precast monolithic girder design rather than a design based on segments.

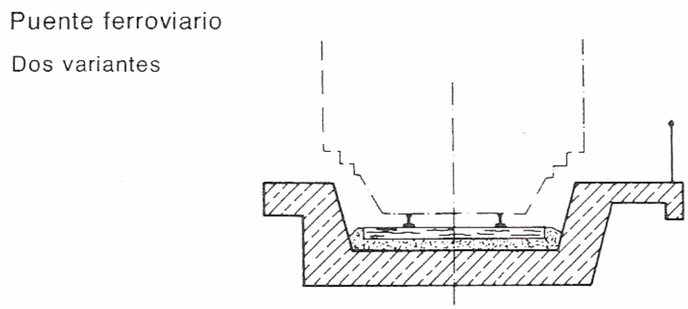

Fig. 8.21. Puente con tablero inferior para ferrocarril.

Fig. 3 Railroad Bridge Cross Section per Leonhardt[2]

Metrorrey's design criteria for the elevated viaduct are based on the latest versions of the following specifications:

- AASHTO Standard Specifications for Highway Bridges
- ACI Building Code Requirements for Structural Concrete (ACI-318)
- Sacramento Transit Development Agency – Design Criteria
- Metropolitan Dade County Office of Transportation Administration – Design Criteria

The load effects to be included in the design of the superstructure were:

• Dead Load	• Live Load	• Impact Factor
• Nosing Load	• Centrifugal Force	• Breaking and Acceleration Force
• Derailment Force	• Wind Load	• Thermal Loads
• Rail Break Force	• Seismic Load	

The live load consisted of a train made up of two, three or four standard vehicles (See Fig. 4) per track. The derailment load consisted of the vertical forces generated by one or two standard vehicles with an impact factor of 100% and a horizontal load equal to 40% of the weight of one vehicle located 0.61 meters (2 ft.) above the rail acting along 3 meters (10 ft.) of the parapet. The weight of the typical vehicle is 69,000 kg (76 tons) and its length is 29.56 m (97 ft.)

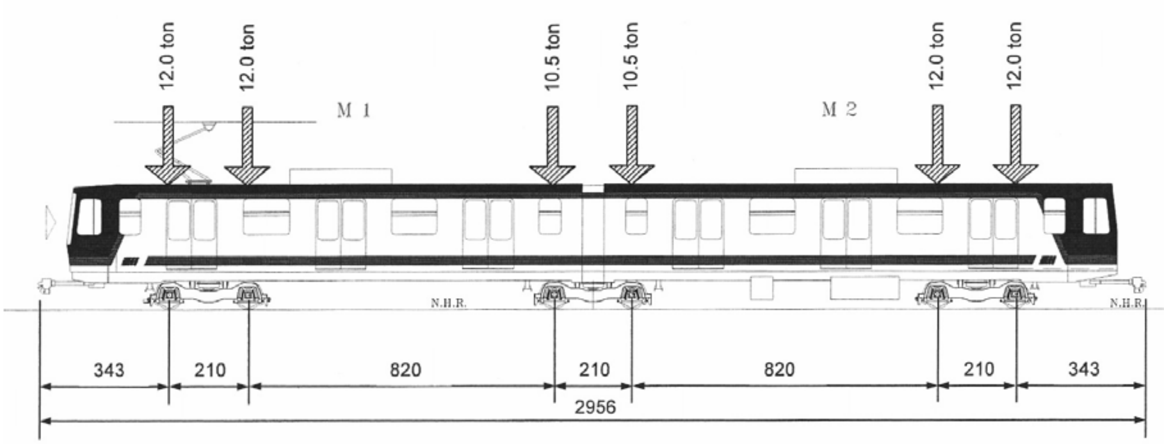

Fig. 4 Metrorrey Standard Vehicle (Dim. in cm. and metric tons)

The design developed for Construction Bidding was based on the designer's (Rioboo S.A.) experience with the Mexico City Metro. The typical superstructure consisted of two types of precast pretensioned beams each 9.2 m wide. Beam type TA was 24 meters (79 feet) long and was integrally attached to two precast columns 12 meter apart (See rendering in Figure 5). Beam TC was 25 meters (82 feet) long and was simply supported (Gerber system) on the 6 meter (19.7 feet) cantilevers created by beam TA. A typical TA girder weighed about 300,000 kg (330 tons) and contained on average 338 kilograms of mild reinforcement per cubic meter of concrete (570 lbs/CY). The typical cross section of the superstructure is shown in Figure 6.

Fig. 5 Rendering of Construction Contract Structural System

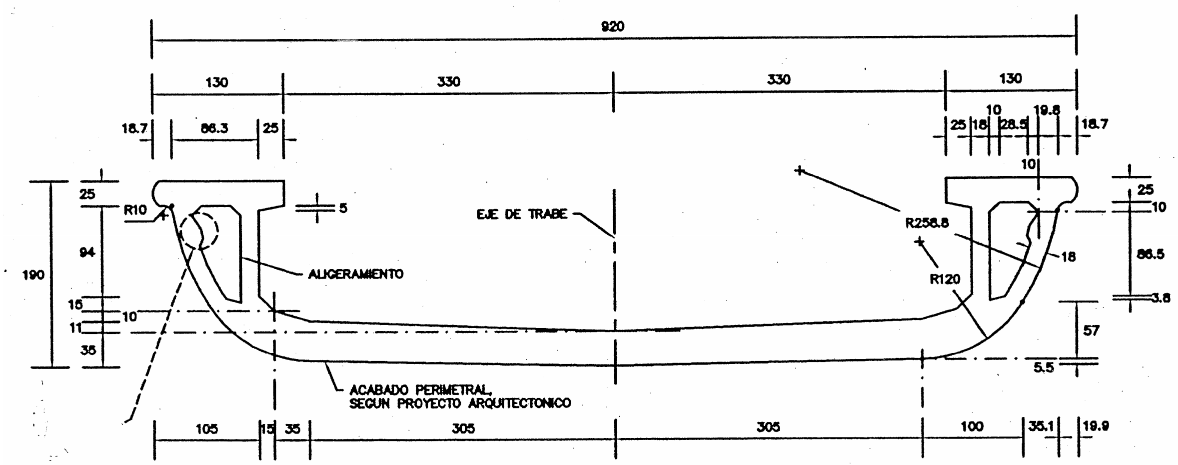

Fig. 6 Typical Cross Section of Construction Contract Typical Girder TA (Dim. in cm)

This system (monolithic single “Omega” beam) is similar to that use in the Modena viaduct built for the Milan-Modena High Speed Line (See Figure 7)

Fig. 7. “Omega” Monolithic Girder for the Modena Viaduct

ALTERNATIVE DESIGN OF THE LINEA 2 EXTENSION

To accelerate the construction of the viaduct, the Contractor (Siemens-Bonbardier- Grupo Garza Ponce) proposed an alternative design based on an innovative concrete segmental technology developed by the first author of this paper. Although Metrorrey's management had previously disregarded the use of segments due to aesthetic considerations, a presentation of aesthetic details (lack of shear key geometry on the surface of webs, use of coatings and methods to assure the uniformity in the color of the segments) on recent segmental projects in the USA convinced Metrorrey's management that the aesthetic deficiencies of Linea 1 would be avoided in the extension of Linea 2. In addition to speed up the construction, the alternative design also permitted an economy of materials, labor, equipment and maintenance of traffic operations. For instance, while the original design had 2 columns every 49 meters (161 feet), the new design has 1 column every 37 m. (121 feet) resulting in an average reduction of 34% in the number of columns. A model of the typical structural system is shown in Figure 8.

Fig. 8 Model of Alternative Structure

RELEVANT FEATURES OF THE TYPICAL STRUCTURAL UNIT

The viaduct's typical structural unit is a simply supported concrete segmental girder resting on 1.6 m (5.25 feet) diameter columns directly attached to 1.8 m (6 feet) drilled shafts without the need of a footing. The girder is 9.2 meters (30.2 feet) wide with a span of 37 meters (121.4 feet). Steel laminated elastomeric bearings separated 4 meters apart provide a flexible connection between the girder and the capital.

SUBSTRUCTURE

The subsurface conditions comprise alluvial deposits of clay, sand, gravel (highly cemented in many cases) overlying a sedimentary rock (locally called "lutita") that are ideal for spread footings or single shafts. The 1.8 m (2.0 m in some cases) drilled single shafts supporting the viaduct columns are typically supported by the cemented conglomerates or the sedimentary rock with lengths ranging from 12 m. (39 feet) to 32 m. (105 feet). These are the largest shafts ever built in Monterey to date. Previously, as in the case of Linea 1, drilled shafts in Monterrey had at most a diameter of 1.20 m. (4 ft.) and were constructed in groups with a footing to support a single column. The positive experience (in terms of economy, constructability, maintenance of traffic and quality control) provided by these large shafts indicates that they will become standard in the future to support large loads on the strong soils found all around the region.

The 1.6m. (5.25 feet) columns support an aesthetically pleasing capital 5.9 meter (19.4 feet) by 2.8 meter (9.2 feet) (See Figure 9). The columns' height ranges from 8 meters (26.2 feet) to about 15 meters (49.2 feet).

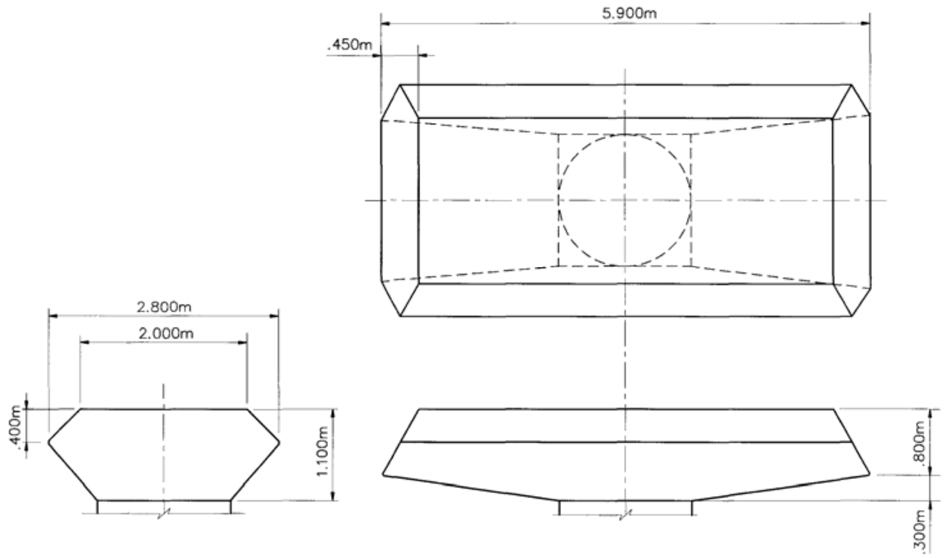

Fig. 9 Typical Capital Dimensions (in meters)

Fig. 10 Typical Laminated Elastomeric Bearings

The concrete segmental girder rests on square 0.5 m. wide (1.64 ft,) laminated elastomeric pads on top of concrete pedestals (See Figure 10). These transversally and longitudinally flexible pads have the advantages of being very economical and decrease the loads applied to the substructure due to seismic loads and rail-structure interaction (differential temperature, creep and rail break). For seismic forces (which are low in this area of Mexico near Texas) the neoprene bearings act like seismic isolators. In the case of the potential large forces due to rail break, the elastomeric bearings reduce the stiffness of the substructure system and transfer most of the load to the other three rails. Consequently the force transmitted to the substructure at the level of the capital relatively small and does not cause a very large moment at the bottom of the column or in the shaft.

The 4 meter (13 feet) distance between the bearing pads is more than adequate to eliminate any uplift due to unsymmetrical loading on the superstructure. Most conventional segmental concrete box girders developed for light rail have very narrow bottom slabs (even when they support two tracks) and require positive connections (steel tie-downs) to the substructure with the associated steel plates. These elements tend to be a maintenance and aesthetic (rust on columns) issue. In the case of the Metrorrey Linea 2 there is no exposed steel at the top of the piers. Photographs of the substructure during construction are shown below (Figure 11).

Fig 11 Substructure Views

SUPERSTRUCTURE SCHEME

The typical concrete segmental simply supported girder has a width of 9.2 meter (30 ft.) and a span of 37 meters (121.4 ft.) (See Figure 12). The cross section was generated to resemble the exterior of the cross section in Figure 5 while eliminating the voided web scheme (See Fig. 6). In addition, the cross section also has the same depth, 1.9 m. (6.17 ft.) as the original design.

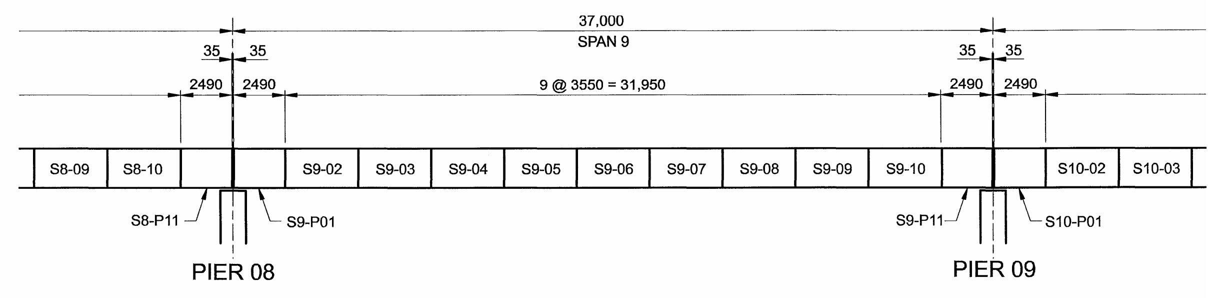

Fig 12 Typical Span Segment Layout (Dim. in mm.)

A typical span 37 m. (121.4 ft.) in length is comprised on 9 typical precast segments 3.55 meters (11.64 feet) long and two pier segments 2.49 m. (8.17 feet) long. With this layout the typical cast in place joint between the pier segments and their associated typical segments does not exist. Between spans there is a 7 cm (2.75 in.) expansion joint gap. The concrete strength for the superstructure is 350 Kg/cm^2 (5000 psi). Furthermore, Metrorrey required a minimum of 5 kg/cm^2 (71 psi) of residual compression for any service load. Actual AASHTO Specifications specify zero tension for this type of scheme (Segments with epoxy joints).

TYPICAL CROSS SECTION

The typical cross section is shown in Figure 13. The bottom slab has a thickness that ranges from 30 cm (11.8 in.) at the sides and 25 cm (9.8 in.) at the center. The side walls have a thickness of 30 cm. (11.8 in.). The total section area is 3.77 m^2 (40.56 ft^2) and the weight of the typical segment is about 32,000 kg. (35 tons).

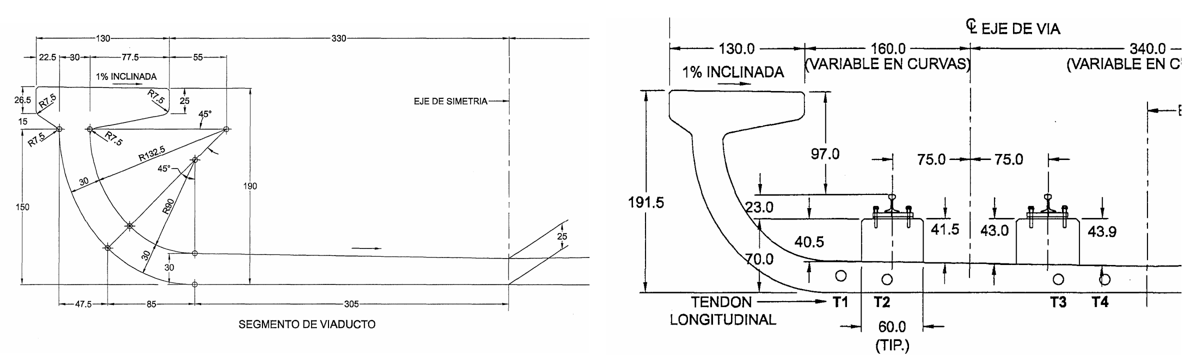

Fig. 13 Typical Cross Section (Dim. in cm.)

The segment shape, based on the shape of the original design, was modified to simplify its dimensions, accommodate the internal forces caused by the loads (especially dead load, live load and derailment) and facilitate its casting and erection. Although the shape of the segment looks remarkably close to that used in the Santiago de Chile metro (See Figure 2), it was developed without prior knowledge of that project. This helped to follow a different design path that generated the unique features of the Metrorrey Linea 2 viaduct. Figure 14 shows a typical segment with the depiction of its cross section.

Fig. 14 Typical Segment and Cross Section

For practical purposes a 37 m (121.4 ft.) span with the cross section shown above acts as a simple beam and can be analyzed by hand to design the longitudinal post-tensioning and reinforcing needed to resist dead loads, live loads and derailment loads. Similarly, to design the cross section for shear and torsion effects, the theories for open cell cross sections (Saint-Venant and Warping torsion) are very suitable in this case (Kollbrunner and Basler[3]). The properties of the cross section are given in Fig 15

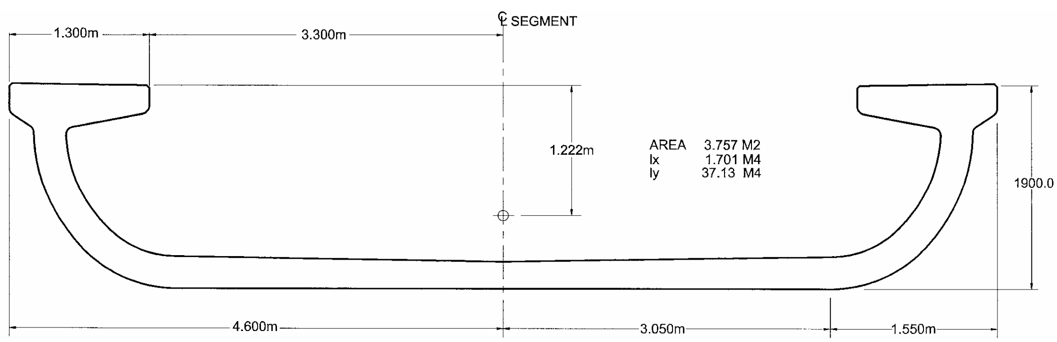

Fig. 15 Typical Cross Section Properties and Center of Gravity

Nevertheless, it is necessary to develop very detailed finite element models to evaluate the local effects of live loads on the bottom slab of the typical segment and to evaluate the forces in the pier segment due to the transmission of web forces to the bearings. Two models of a complete typical 37 m (121 ft.) span were developed using three-dimensional elements. The first model represented only the structure without the rail plinth to evaluate the loads created by them and the self weight of the segments. The second model represented the structure acting composite with the rail plinths to evaluate the effects of the rails and the live load. In the case of the live load (wheels point loading), it is very important to account for the lateral and longitudinal distribution (and, consequently, the reduction of the bottom slab stresses) of the loads provided by the stiffness of the rails, the rail anchors and the rail plinths. Figures 16 and 17 show a plot of the results of the finite element analysis at the center of the span.

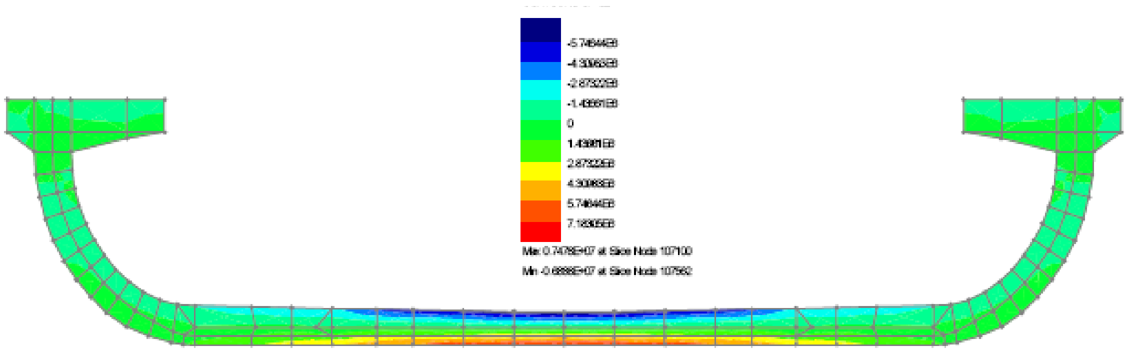

Fig. 16 Transverse Stresses at Mid-Span Due to Self Weight and Plinth Weight

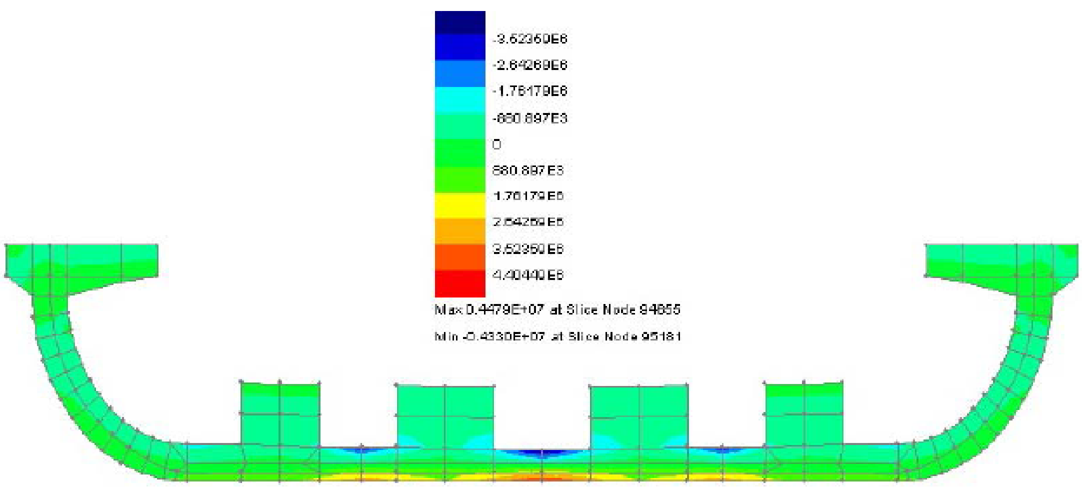

Fig. 17 Transverse Stresses at Mid-Span Due to Live Load

The longitudinal post-tensioning required for a typical span comprises 8 tendons with 17 strands each located at the bottom slab and 2 tendons with 6 strands located at the top flanges (Figure 14) without tendons located at the webs. Each strand has a 15.7 mm diameter (0.618 in) and a ultimate capacity of 19,000 kg/cm^2 (270 ksi). Flange tendons are straight and bottom slab tendons are also straight with a slight upwards turn at the pier segment to accommodate the dimensions of the anchors (Figure 18). The two top flange tendons are needed to accommodate the tensile stresses at the top slab near the expansion joints due to the positive moments developed by the bottom slab tendons. In addition they improve the integrity of the top flanges against lateral loads (derailment) applied to them.

Fig. 18 Typical Tendon Anchorages at Pier Segment

This longitudinal tendon layout (similar to that typically used in precast AAHTO girders) is very cost effective in terms of labor (both in the casting yard and at the field during erection) due to its simplicity. Typically, the tendon layout used in the past with this type of cross section include tendons anchored in the web as indicated in Figures 2 and 19). This may be one of the reasons why this type of cross section has not been used more often in the past. Furthermore, this tendon layout also has similar advantages over the typical variable depth external tendon layout found in precast segmental box girders built span-by-span. In addition the innovative constant depth tendon layout developed for the Metrorrey concrete segmental project allows the use of a thin constant thickness web and the use of a relative small, 60 cm (24 in.) deep, and very constructable bottom slab diaphragm to anchor the tendons.


Fig. 19 Modena Viaduct Tendon Layout

Typically, concrete segmental box girder bridges for light rail contain about 24.4 kg of longitudinal post-tensioning steel per square meter of bridge deck (5.0 lbs/SF). For instance, MARTA Project CF310 contains 27.4 kg/m^2 (5.61 lbs/SF). In the case of the Linea 2 Metrorrey project that value is only 20.2 kg/m^2 (4.14 lbs/SF). In terms of concrete quantities for a given square foot of deck, concrete segmental box girder bridges for light rail contain about 0.53 cubic meters of concrete per square meter of bridge deck (1.75 ft^3/ft^2). For instance MARTA Project CF310 contains 0.57 m^3/m^2 (1.88 CF/SF). In the case of the Linea 2 Metrorrey project that value is only 0.44 m^3/m^2 (1.43 CF/SF), a 25% reduction. These are remarkable results that attest to the substantial economical advantages of this scheme over the previous applications of segmental construction to light rail bridges.

TYPICAL SEGMENT

The typical segment is 3.55 m. (11.54 ft.) long, 9.2 m. (30 ft.) wide and 1.9 meters (6.17 ft.) high. It contains only 13.4 m^3 (17.5 cy) of concrete and 603 kg (1329 lbs) of reinforcing steel. This results in the remarkable ratio of 45 kg/m^3 (76 lbs/CY) of concrete. Commonly, this value is about 120 kg/m^3 (200lbs/CY) for segmental box girder bridges.

These low quantities of reinforcing steel are easily explained by the fact that the reinforcement for the Metrorrey Linea 2 typical segment comprises #3 bars at about 22 cm. (8.66 in.) all over the surfaces of the cross section (See Figures 20 and 21) .

Fig. 20 Typical Segment Reinforcing Cage in Casting Yard

Fig. 21 Typical Segment Reinforcing in Casting Bed

The transverse green elements shown in Figure 21 comprise another remarkable innovation associated with this project: the use of greased-and-sheathed monostrand transverse post-tensioning. Greased-and-sheathed transverse monotrands are needed to obtain small prestressing losses and to provide cost effective post-tensioning forces at the center of the bottom slab (about 65% of G.U.T.S.) after all losses. They have an additional advantage over the typical flat duct 4-strand tendons commonly used in precast segmental boxes because they do not need to be grouted. The transverse tendon layout for a typical segment is shown in Figure 22. In each 3.55 m (11.54 ft.) segment there are 16 15 mm (0.6 in) greased-sheathed monostrands that serve three functions: increase the flexural capacity of the bottom slab under vertical loads, increase the shear capacity of the webs for all loads and increase the bending capacity of the webs for vertical loads and lateral derailment loads. The number of tendons is determined by the need to accommodate the vertical loads in the bottom slab. Their beneficial effect in the webs is what allows the substantially low quantities of reinforcing steel in the segment. The tendons were single-end stressed at alternating ends.

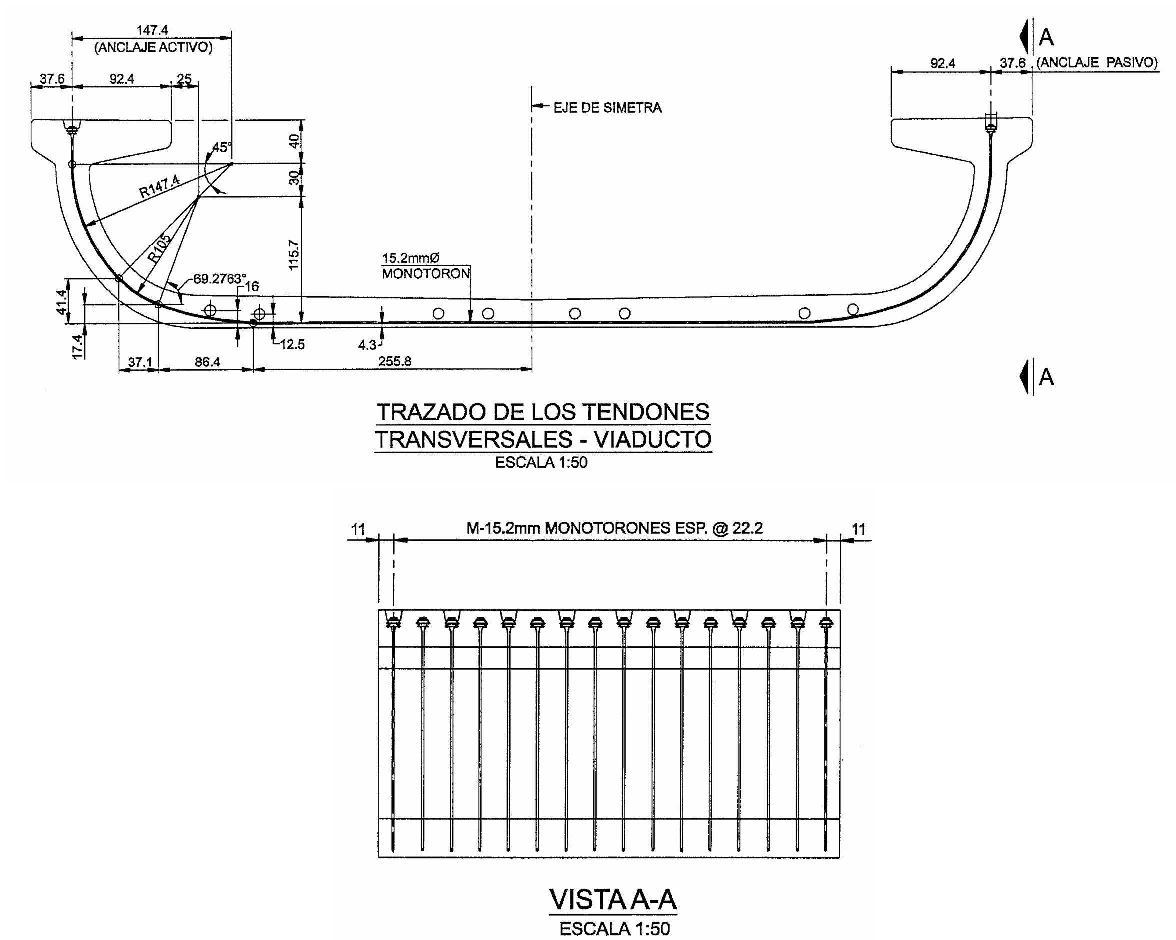

Fig. 22 Typical Segment Transverse Layout (Dim. in cm.)

Another advantage of this innovative use of greased-and-sheathed monostrands is that, if necessary. they can be inspected and replaced. In Metrorrey's Linea 2 Extension project several segments required replacement of the transverse tendons in the casting yard because of faulty prestressing steel (see Figure 23). This was accomplished quickly and effectively.

Fig. 23 Transverse Strand Replacement.

PIER SEGMENT

The pier segments (dimensions are shown in Figure 24) essentially have the same shape as the typical segment. The only difference is the increased thickness of the bottom slab to accommodate the transmission of the shear forces to the bearings and the anchoring of the 8 bottom slab tendons. The segment contains only 13.9 m^3 (18.2 cy) of concrete and 2983 kg (6576 lbs) of reinforcing steel; or a ratio of 214 kg/m^3 (361 lbs/CY) of concrete. Commonly, this value is about 240 kg/m^3 (400 lbs/CY) for segmental box girder bridges for light rail. Several views of the Pier Segment reinforcement are found in Figure 25.

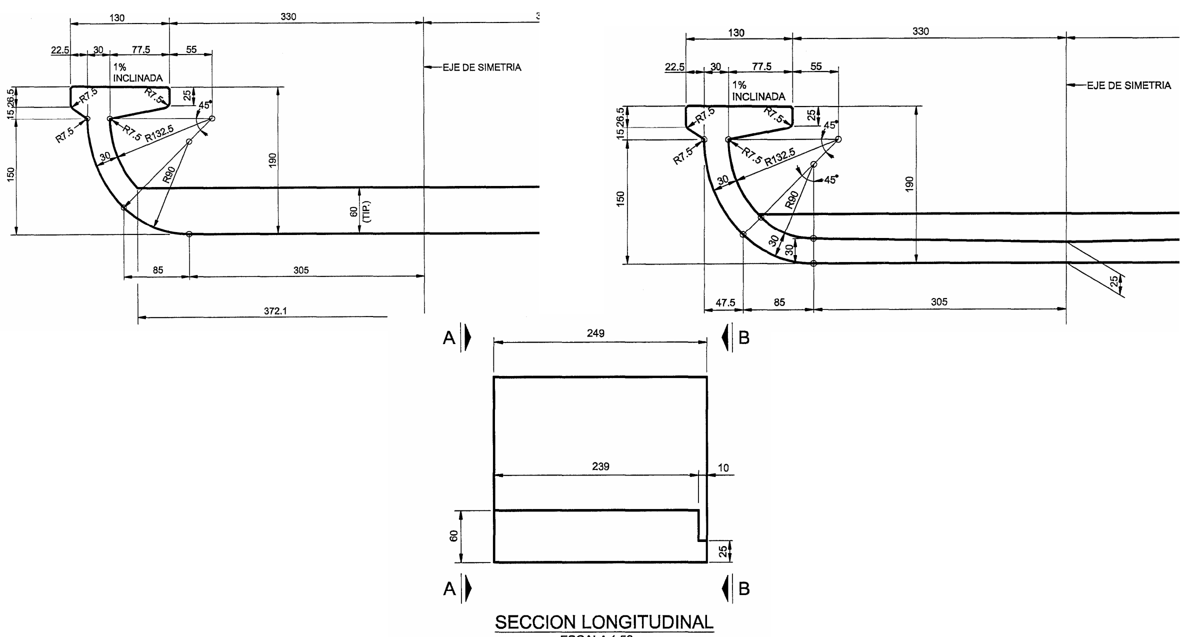

Fig. 24 Pier Segment Dimensions (Dim. in cm.)

Fig. 25 Pier Segment Reinforcement

Fig. 26 Pier Segment Reinforcing Santiago de Chile Metro

Although the pier segment designed for the Metrorrey Linea 2 extension has a relatively large amount of reinforcement, Figure 25 shows that the reinforcing layout allow for a quick assembly and easy concrete placement. The advantages of this design are clear when Figure 25 is compared with Figure 26 (Pier Segment reinforcing for Santiago de Chile project) or an equivalent box girder expansion joint segment. The pier segment is, for practical purposes, a reinforced concrete element strengthened by 13 transverse greased-and-sheathed monostrands that also assist in crack control

SEGMENT CASTING

The segments were cast in the same casting yard that was used for the Linea 1. The contractor decided to use the full span, long-line casting method: casting all the typical segments for each span adjacent to one another in a single bed in the same relative positions they will occupy when erected in the bridge. This method was previously selected by the late Jean Muller for the MARTA 360 and the Metrorrey Linea 1 segmental box girder light rail projects. In the case of the Linea 2 Extension, the shape of the cross section and the use of greased-and-sheathded strands simplify both the casting forms and the labor needed to cast and stress the tendons (which is done while the segments are on the casting bed and not in the storage yard). Figure 27 shows several views of the casting of typical segments.

Fig. 27 Casting Beds for Typical Segments

The pier segments are cast against its associated typical segment in a short bed. Figure 28 shows several views of the casting of pier segments and the structural details internal to the segment.

Fig. 28 Pier Segment Casting.

TYPICAL SPAN ERECTION

The erection subcontractor (VSL) selected to erect the spans with two overhead gantries, the same ones that erected the Santiago de Chile Viaduct. Figure 29 show several views of the gantries and the erection process

Fig. 29 Segment Erection Views

The yellow-colored gantry rolled over the erected span to move to erect the next span. The rear leg was supported on wheels rolling over the bottom slab (Figure 29 bottom views). The total point load to be supported was 92,000 kg (202 tons). This load case was also studied using finite elements. The other gantry (blue colored) always placed its loads at the location of the piers.

COMPLETED STRUCTURE

Several views of the typical spans are shown below (Figure 30)

Fig. 28 Views of Completed Spans

LESSON LEARNED AND FUTURE DEVELOPMENTS

The segmental superstructure developed by the first author for the Linea 2 Extension of the Monterrey metro has multiple remarkable advantages over the segmental box girder superstructures typically used for light rail projects in terms of material quantities, casting labor cost, and erection labor costs. The lessons learned from its design predict the success of the following future developments:

- **Complete elimination of the reinforcing steel in the superstructure (at least in the typical segments) by incorporating fiber-reinforced concrete.**

- **Application of the system to balanced cantilever superstructures for long spans.** One potential scheme for the "Omega" or "U' cross section has been already implemented in the Modena Viaduct (Figure 31).

Fig. 31 Long Span Superstructure Scheme for the Modena Viaduct

CONCLUDING REMARKS

This paper has demonstrated the advantages of using a "U" or "Omega" cross section combined with transverse and longitudinal post-tensioning for concrete segmental light rail viaducts. The future use of this technology will depend mostly on the acceptance by owners, designers and contractors of a concrete structure almost without reinforcing bars and almost fully strengthened by post-tensioning in three directions: horizontally, transversally and vertically. Among the advantages of the system with respect to the typical box girder superstructure are the following:

1. Lower material quantities.
2. Lower segment fabrication costs in terms of forms, reinforcing cage assembly, post-tensioning and casting labor.
3. Lower span erection costs and time due to the lack of cast-in-place joints between pier and typical segment.
4. Shallower elevation profile of the superstructure-vehicle system.
5. Intrinsically more stable against turn-over thanks to its wide bottom slab.
6. Lower bearing costs due to the use of elastomeric bearings without tie downs and steel plates.
7. Greater security against derailment due to vehicle confinement by the “U” section.
8. Elimination of the typically heavy and non-structural noise walls

The viaduct of the Linea 2 Extension is an aesthetically pleasing state-of-the art structure that offers an innovative application of proven post-tensioning and concrete segmental technologies that stretches the materials in a new direction. The structure also shows how existing proven techniques and materials can work in synergy to develop a low cost, high quality and esthetically pleasing light rail bridge superstructure with almost no reinforcing steel.

Note: Some of the line drawings used herein were taken directly from the project’s contract drawings which were contractually required to be in Spanish. This may have caused some inconvenience to non-Spanish speaking readers but it also provides examples for the readers to compare with common contract drawing layout in the USA The authors feel that enough can be understood from the drawings to make the intent self-explanatory.

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CREDITS

Owner:	STC Metrorrey
Contractor	Siemens – Bombardier – Grupo Garza Ponce
Erection Subcontractor:	VSL
Post-tensioning Supplier	VSL
Prime Consultant:	Weidlinger Associates Inc.
Author Viaduct Structural System	Juan Jose Goni, PhD, PE, Garcia Bridge Engineers, PA
Geotechnical Engineer:	TGC Geotecnia

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