Metrorrey's linea 2 extension viaduct: A revolution for light-rail precast concrete segmental bridges

Juan José Goñi Baamonde and Antonio M. García y Benitez

In 1991, the 18.5-km-long (11.6 mi) linea 1, the first line of the Metro of Monterrey (Metrorrey), was completed and opened to the public in the metropolitan area of Monterrey, Nuevo Leon, Mexico. The precast concrete segmental structure (**Fig. 1**) was designed by the late Jean Muller.[1] The structure comprises typical simple spans about 27 m (89 ft) long with a maximum span length of 36 m (118 ft). The box girders have a width of 7.40 m (24.3 ft) and a depth of 2.13 m (7.0 ft).

While this viaduct is an efficient system for transporting people, the existing structure has serious aesthetic deficiencies: wavy segment joints, rust in the columns, and a lack of uniformity in the color of the segments. These problems have prompted negative comments from the citizens and motivated Metrorrey to explore alternative concepts for the linea 2 extension.

Editor's quick points

- The Metro of Monterrey's new 6.6-km-long (4.1 mi) linea 2 extension viaduct in Monterrey, Mexico, includes a revolutionary concept for precast concrete segmental light-rail bridges.
- The concept offers a viable and more economical alternative to the typical box-girder cross sections for light-rail bridges.
- This paper was originally presented at the 2007 PCI Convention and National Bridge Conference and was a 2008 PCI Design Award winner for Best Non-highway Bridge.

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

Figure 1. The precast concrete segmental structure used for the Metrorrey linea 1 concrete segmental viaduct was designed by the late Jean Muller.

congested downtown. To extend the line northward, 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, Chile, and Taiwan metros could help to resolve the aesthetic deficiencies of the previous project. Leonhardt[2] had previously suggested this cross section for railway bridges. Avoiding negative input from those affected was critical for acquiring the necessary permits and capital to complete the project bridges.

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. In addition, the distance between the tops 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 broken) in linea 1, a monolithic precast concrete girder design was used, rather than a design based on segments.

Metrorrey's design criteria for the elevated viaduct were primarily based on the latest versions of the American Association of State Highway and Transportation Officials' (AASHTO's) *Standard Specifications for Highway Bridges*[3] and the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05)*[4].

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 forces, derailment force, wind load, thermal load, rail break force, and seismic load.

The live load consisted of a train of two, three, or four standard vehicles per track (**Fig. 2**). 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 m (2.0 ft) above the rail acting along 3 m (10 ft) of the parapet. A typical vehicle weighs 69,000 kg (76 tons), and is 29.6 m (97 ft) long.

The design developed for construction bidding was based on the designer's experience with the Mexico City, Mexico, Metro. The typical superstructure consisted of two types of precast, pretensioned concrete beams, each of which were 9.2 m (30 ft) wide. Beam type TA was 24 m (79 ft) long and was integrally attached to two precast concrete columns spaced 12 m (39 ft) apart. Beam TC was 25 m (82 ft) long

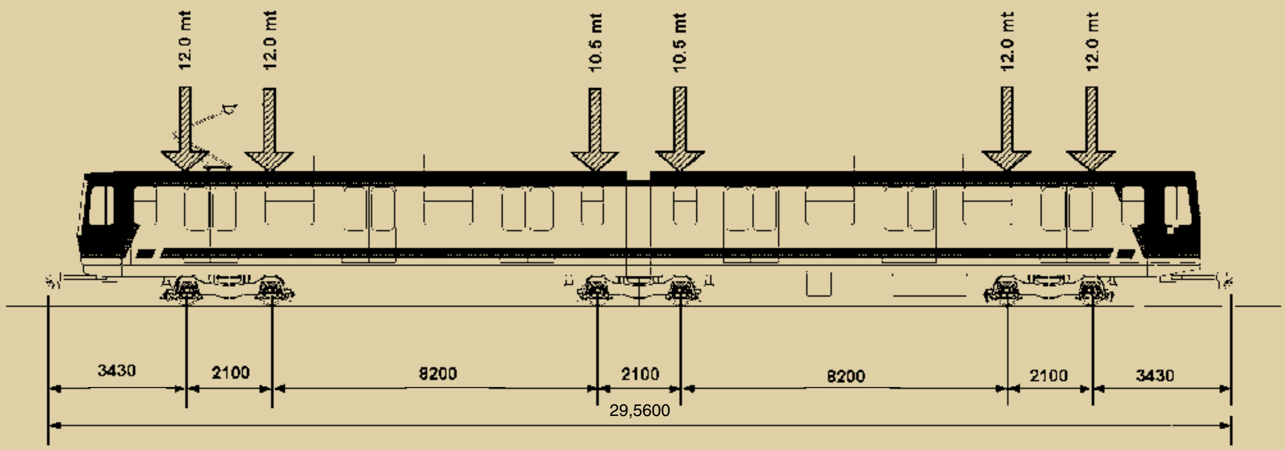

Figure 2. This diagram illustrates the Metrorrey standard vehicle. Source: Reprinted by permission from Metrorrey. Note: All length measurements are in millimeters. 1 mm = 0.0394 in.; 1 mt = 1.10 tons.

and was simply supported with a Gerber system on the 6-m-long (20 ft) cantilevers created by beam TA.

A typical TA girder weighs about 300,000 kg (330 tons) and contains on average 338 kg of mild reinforcement per cubic meter of concrete (570 lb/yd^3). **Figure 3** shows the typical cross section of the superstructure, which is a monolithic, single U-shaped beam. This system is similar to that used in the Modena viaduct built for the Milan-Modena high-speed line in Italy.

Alternative design of the linea 2 extension

To accelerate the construction of the viaduct, the contractor proposed an alternative design based on an innovative precast concrete segmental technology developed by Juan José Goñi Baamonde. Although Metrorrey's management had previously disregarded the use of segments due to aesthetic considerations, a presentation of aesthetic details (that is, the lack of shear-key geometry on the surface of webs, the use of coatings, and the use of methods to ensure color uniformity of the segments) on recent segmental projects in the United States convinced Metrorrey's management that the aesthetic deficiencies of linea 1 would be avoided in the extension of linea 2.

In addition to accelerating the construction of the project, the alternative design also provided an economy of materials, labor, and equipment and permitted for the maintenance of traffic operations. For instance, while the original design had two columns every 49 m (161 ft), the new design had one column every 37 m (121 ft), resulting in an average reduction of 34% in the number of columns.

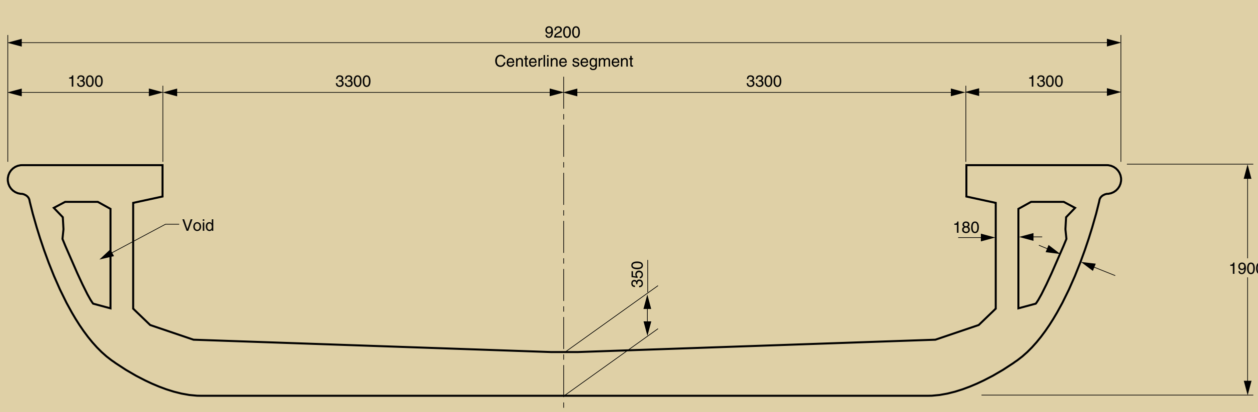

Figure 3. This diagram shows a typical cross section of girder TA, which was used in the construction of the light-rail system. Note: All measurements are in millimeters. 1 mm = 0.0394 in.

Figure 4. This photo shows the substructure of Metrorrey linea 2 during construction.

Relevant features of the typical structural unit

The viaduct's typical structural unit is a simply supported precast concrete segmental girder resting on 1.6-m-diameter (5.2 ft) columns directly attached to 1.8-m-long (5.9 ft) drilled shafts, which do not require a footing. The girders are 9.2 m (30 ft) wide with a span of 37 m (121 ft). Steel-laminated elastomeric bearings spaced 4 m (13 ft) apart provide a flexible connection between the girder and the capital.

Substructure

The subsurface conditions include alluvial deposits of clay, sand, and gravel (highly compacted in many cases) overlying sedimentary rock, and they are ideal for spread footings or single shafts. The 1.8 m (5.9 ft) (2.0 m [6.6 ft] 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 to 32 m (39 ft to 105 ft). These are believed to be the largest shafts ever built in Monterrey to date.

Previously, as in the case of linea 1, drilled shafts in Monterrey had at most a diameter of 1.2 m (3.9 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 around the region.

The 1.6-m-diameter (5.2 ft) columns support an aesthetically pleasing capital that is 5.9 m × 2.8 m (19 ft × 9.2 ft). The columns' heights range from 8 m to 15 m (26 ft to 49 ft).

The precast concrete segmental girders rest on 0.5-m-square (1.6 ft) laminated elastomeric pads on top of concrete pedestals. These transversely and longitudinally flexible pads are economical and decrease the loads applied to the substructure due to seismic loads and rail-structure interaction, such as differential temperature, creep, and rail break. For seismic forces, which are low in this area of Mexico, 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 is relatively small and does not cause a large moment at the bottom of the column or in the shaft.

The 4 m (13 ft) distance between the bearing pads is more than adequate to eliminate any uplift due to unsymmetrical loading on the superstructure. Most conventional segmen-

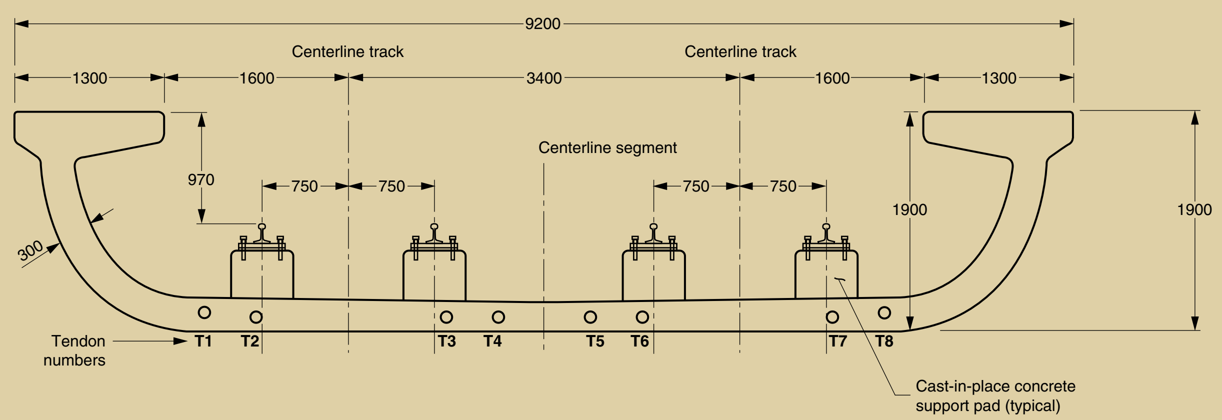

Figure 5. This diagram illustrates the typical cross-section dimensions. Note: All measurements are in millimeters. 1 mm = 0.0394 in.

tal concrete box girders developed for light rail have narrow bottom slabs even when they support two tracks and require positive connections, such as steel tie-downs, to the substructure with associated steel plates. These elements tend to create issues with maintenance and aesthetics, often causing rust on the columns. In the design of the Metrorrey linea 2, there was no exposed steel at the tops of the piers. **Figure 4** shows the substructure during construction.

Superstructure scheme

A typical precast concrete segmental simply supported girder has a width of 9.2 m (30 ft) and a span of 37 m (121 ft). The cross section was created to resemble the exterior of the cross section in Fig. 3 while eliminating the voided web scheme. In addition, the cross section also has the same depth as the original design, 1.9 m (6.2 ft).

Figure 6. This photo shows a typical segment with a clear view of the cross section.

Figure 7. This photo shows the typical pier segment and highlights some of the anchoring.

A typical 37-m-long (121 ft) span includes nine 3.55-m-long (11.6 ft) typical precast concrete segments and two 2.49-m-long (8.17 ft) pier segments. With this layout, the typical cast-in-place concrete joint between the pier segments and their associated typical segments does not exist. Between spans there is a 70-mm-thick (2 $^3/_4$ in.) expansion-joint gap. The concrete strength for the superstructure is 35 MPa (5 ksi). Furthermore, Metrorrey required a minimum of 5 kPa (70 psi) of residual compression for any service load. Actual AASHTO standard specifications specify zero tension for this type of scheme, that is, segments with epoxy joints.

Typical cross section

Figure 5 shows the typical cross section. The bottom slab has a thickness that ranges from 300 mm (12 in.) at the sides to 250 mm (9.8 in.) at the center. The side walls have a thickness of 300 mm. The total section area is 3.77 m^2 (40.6 ft^2), and the weight of the typical segment is about 32,000 kg (35 tons).

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. This enabled a different design path that generated the unique features of the Metrorrey linea 2 viaduct. **Figure 6** shows a typical segment with the depiction of its cross section.

For practical purposes, a 37 m (121 ft) span with the cross section shown in Fig. 5 acts as a simple beam and can be analyzed by hand to design the longitudinal post-tensioning and reinforcement 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 (that is, Saint-Venant and warping torsion) are suitable in this case.[5]

Nevertheless, it is necessary to develop 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 compositely with the rail plinths to evaluate the effects of the rails and the live load. In the case of the live load (wheels acting as point loads), it is 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.

Figure 8. A typical segment of the Metrorrey linea 2 contains 10M (no. 3) reinforcing bars at a spacing of about 220 mm (8.7 in.) across the entire surface of the cross section.

The longitudinal post-tensioning required for a typical span includes 8 tendons with 17 strands each located in the bottom slab and 2 tendons with 6 strands each located in the top flanges (Fig. 6) with no tendons in the webs. Each 15.7-mm-diameter (0.618 in.) strand has an ultimate capacity of 1860 MPa (270 ksi). Flange tendons are straight, and bottom-slab tendons are straight with a slight upward turn at the pier segment to accommodate the dimensions of the anchors (**Fig. 7**). 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).

This longitudinal tendon layout (similar to that typically used in AASHTO precast concrete girders) is cost effective in terms of labor (both in the casting yard and at the field during erection) due to its simplicity. The tendon layout used in the past with this type of cross section typically included tendons anchored in the web. This difficult layout may be one reason that this cross section was not used more frequently in the past. The simpler tendon layout has similar advantages over the typical variable-depth external-tendon layout found in precast concrete 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 constructable, 600-mm-deep (24 in.) bottom-slab diaphragm to anchor the tendons.

Typically, precast 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 lb/ft^2). For instance, Metropolitan Atlanta Rapid Transit Authority (MARTA) project CF310 contains 27.4 kg/m^2 (5.61 lb/ft^2). However, the linea 2 Metrorrey project has only 20.2 kg/m^2 (4.14 lb/ft^2).

In terms of concrete quantities for a given square foot of deck, precast concrete segmental-box-girder bridges for light rail contain about 0.53 m^3 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 ft^3/ft^2), but the linea 2 Metrorrey project has only 0.44 m^3/m^2 (1.43 ft^3/ft^2)—25% less. These are remarkable results that attest to the substantial economical advantages of this scheme over the previous applications of segmental construction of light-rail bridges.

Typical segment

The typical segment is 3.55 m (11.5 ft) long, 9.2 m (30 ft) wide, and 1.9 m (6.2 ft) high. It contains only 13.4 m^3 (17.5 yd^3) of concrete and 603 kg (1330 lb) of reinforcing steel. This results in a ratio of 45 kg/m^3 (76 lb/yd^3) of steel

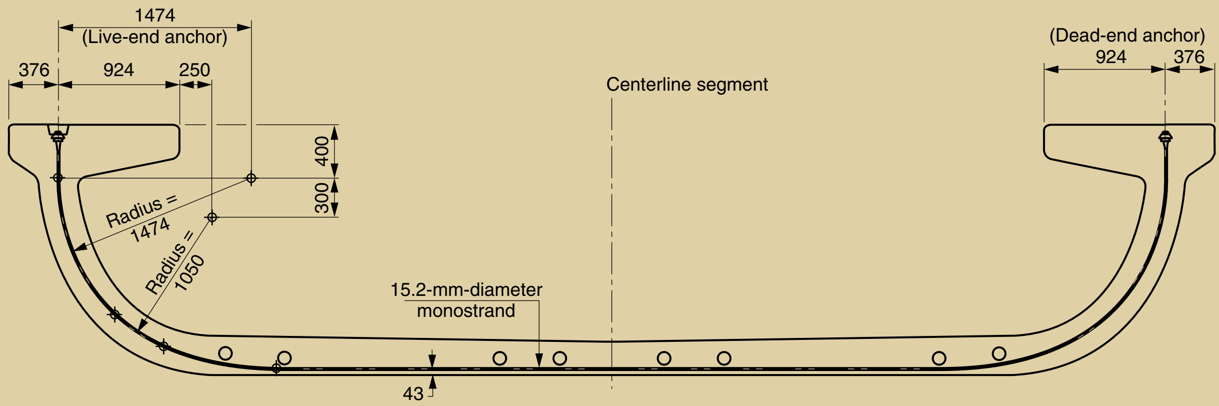

Figure 9. This diagram illustrates the transverse tendon layout. Note: All measurements are in millimeters. 1 mm = 0.0394 in.

weight to concrete volume. Commonly, this value is about 120 kg/m^3 (200 lb/yd^3) for precast concrete segmental-box-girder bridges. This low quantity of reinforcing steel is explained by the fact that the reinforcement for the Metrorrey linea 2 typical segment contains 10M (no. 3) reinforcing bars at a spacing of about 220 mm (8.7 in.) across the entire surface of the cross section (**Fig. 8**).

The green transverse elements in Fig. 8 compose another remarkable innovation associated with this project: the use of greased and sheathed monostrand transverse post-tensioning. Greased and sheathed transverse monostrands are needed to obtain small prestressing losses and to provide cost-effective post-tensioning forces at the center of the bottom slab after all losses (about 65% of guaranteed ultimate tensile strength). Unlike the typical flat-duct, four-strand tendons commonly used in precast concrete segmental box girders, they do not need to be grouted. **Figure 9** shows the transverse tendon layout for a typical segment.

In each 3.55-m-long (11.6 ft) segment, there are sixteen 15-mm-diameter (0.6 in) greased and sheathed monostrands that serve three functions: increasing the flexural capacity of the bottom slab under vertical loads, increasing the shear capacity of the webs for all loads, and increasing 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.

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

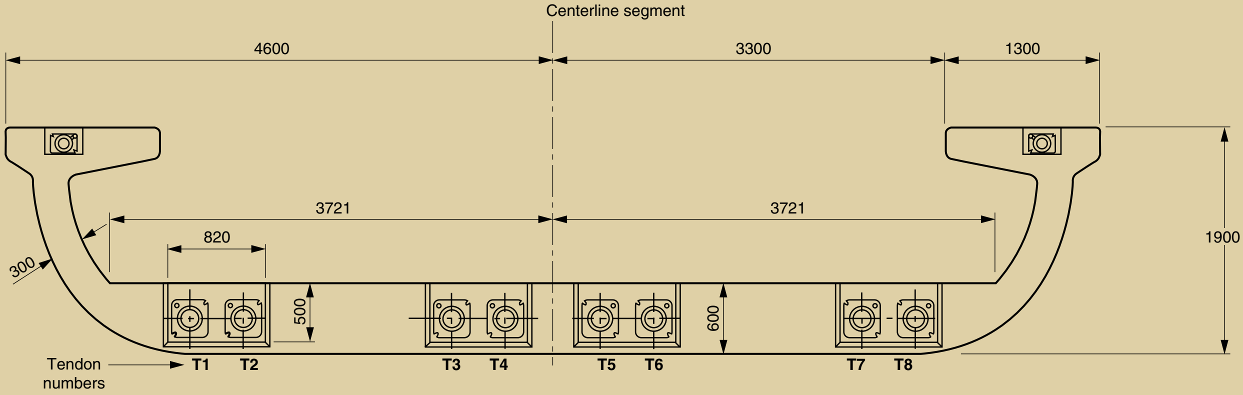

Figure 10. The pier segments have essentially the same shape as the typical segment except for an increased thickness of the bottom slab to accommodate the transmission of the shear forces to the bearings and the anchoring of the eight bottom-slab tendons. Note: All measurements are in millimeters. 1 mm = 0.0394 in.

Figure 11. This photo shows the pier segment reinforcement.

Figure 12. The shape of the cross section and the use of greased and sheathed strands simplified both the casting forms and the labor needed to cast and stress the tendons.

Figure 13. The pier segments were cast against their associated typical segment in a short bed.

Pier segment

The pier segments (**Fig. 10**) have essentially 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 eight bottom-slab tendons. The segment contains only 13.9 m^3 (18.2 yd^3) of concrete and 2983 kg (6576 lb) of reinforcing steel, a ratio of 214 kg/m^3 (361 lb/yd^3) of steel weight to concrete volume. Commonly, this value is about 240 kg/m^3 (400 lb/yd^3) for precast concrete segmental-box-girder bridges for light rail. **Figure 11** shows a view of the pier segment reinforcement.

Although the pier segment designed for the Metrorrey linea 2 extension has a relatively large amount of reinforcement, the reinforcement layout allows for quick assembly and easy concrete placement. 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 project. The contractor used the full-span, long-line casting method, which consisted of casting all of the typical segments for each span adjacent to one another in a single bed in the same relative positions that they would occupy when erected in the bridge. This method was previously used 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 sheathed strands simplified both the casting forms and the labor needed to cast and stress the tendons. **Figure 12** shows a view of the casting of typical segments. The pier segments were cast against their associated typical segment in a short bed. **Figure 13** shows a view of the casting of pier segments and the structural details internal to the segment.

Typical span erection

The spans were erected with two overhead gantries, the same ones that erected the Santiago viaduct. **Figure 14** shows a view of one of the gantries during erection of the first span.

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

Figure 14. The spans were erected with two overhead gantries.

Figure 15. The completed spans here are on high-level piers.

Figure 16. The completed spans here are on low-level piers.

Completed structure

The section of the line comprising the first three stations was opened for service in October 2007. The remainder was opened in October 2008. A typical day's ridership in the Metrorrey system when the project started in August 2005 was about 190,000 passengers. The additional 8.5 km (5.1 m) of the linea 2 has increased that number to 430,000, more than double the number of users for a 25% increase in the length of Metrorrey's system. **Figures 15** and **16** show views of the completed viaduct.

Future developments

The segmental superstructure developed for the Metrorrey linea 2 extension has multiple advantages over the segmental-box-girder superstructures typically used for light-rail projects in terms of material quantities, casting labor costs, and erection labor costs. The lessons learned from its design predict the success of future developments:

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

- The system can be applied to balanced-cantilever superstructures for long spans. One potential scheme for the U-shaped cross section has already been implemented in the Modena viaduct.

Conclusion

This paper has presented the success of the use of a U-shaped cross section combined with transverse and longitudinal post-tensioning for precast concrete segmental light-rail viaducts. The future use of this technology will depend on the acceptance by owners, designers, and contractors of a concrete structure with minimal mild reinforcing bars, which is almost fully strengthened by post-tensioning in three directions: horizontally, transversely, and vertically. There are many advantages of the system with respect to the typical box-girder superstructure:

- lesser material quantities

- lesser segment fabrication costs in terms of forms, reinforcing-cage assembly, post-tensioning, and casting labor

- lesser span erection costs and time due to the lack of cast-in-place concrete joints between the pier and typical segments

- shallower elevation profile of the superstructure-vehicle system

- intrinsically more stable against turnover because of its wide-bottom slab
- lower bearing costs because of the use of elastomeric bearings without tie-downs and steel plates
- greater security against derailment because of vehicle confinement by the U-section
- elimination of the typically heavy and nonstructural 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 precast concrete segmental technologies that stretch 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 aesthetically pleasing light-rail bridge superstructure with almost no mild reinforcing steel.

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References

1. Mondorf, Paul. 1993. Design-Construction of Precast Segmental Elevated Metro Line for Monterrey, Nuevo Leon, Mexico. *PCI Journal*, V. 38, No. 2 (March–April): pp. 42–56.

2. Leonhardt, Fritz. 1979. *Estructuras de Hormigon Armado – Bases para la Construccion de Puentes Monoliticos.* [Spanish translation of the German *Vorlesungen Uber Massivbau*.] Buenos Aires, Argentina: El Ateneo.

3. American Association of State Highway and Transportation Officials (AASHTO). 2002. *Standard Specifications for Highway Bridges*. 17th ed. Washington, DC: AASHTO.

4. American Concrete Institute (ACI) Committee 318. 2005. *Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05)*. Farmington Hills, MI: ACI.

5. Kollbrunner, C. F., and K. Basler. 1969. *Torsion in Structures.* Berlin, Germany: Springer-Verlag.

About the authors

Juan José Goñi Baamonde, PhD, P.E., is vice president of Garcia Bridge Engineers in Tallahassee, Fla.

Antonio M. García y Benitez, P.E., is president of Garcia Bridge Engineers.

Synopsis

Metro of Monterrey's new 6.6-km-long (4.1 mi) linea 2 extension viaduct in Monterrey, Mexico, completed in September 2008, includes a revolutionary concept for precast concrete segmental light-rail bridges developed by Juan José Goñi Baamonde. The 37-m-long (121 ft), 9.2-m-wide (30 ft) typical spans have a U-shaped cross section that allows the two rail tracks to be placed within the structure envelope, which reduces noise, danger of derailment, and visual impact.

In addition, the typical segment contains only 45 kg of structural reinforcement per cubic meter of concrete (76 lb/yd^3) concrete with 10M (no. 3) bars, whereas most current light-rail segmental bridges typically contain concrete with a density of about 120 kg/m^3 (200 lb/yd^3). This was 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

Greased and sheathed, light rail, monostrand, segmental, U-shaped girder, train, transportation.

Review policy

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