PRECAST SEGMENTAL BRIDGES IN RIYADH METRO PROJECT - LINES 1 & 2

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ABSTRACT

The Riyadh Metro Project Lines 1 and 2 is a design and build project which contain over 21 km of precast segmental viaducts. The project has more than 6000 precast concrete segments primarily carrying double, but also single, and triple tracks. Spans vary from 21m to 70m with curved radii as tight as 100m. The method of erection is span-by-span using overhead gantries for the shorter spans, and balanced cantilever using a pair of lifting frames for the longer spans. The project has around 600 piers of various types of cast-in-place concrete founded primarily on drilled shafts. BIM platform has been used in the design.

KEYWORDS: Precast girders, post-tensioned, light rail, metro, viaduct, span-by-span, balanced cantilever, segmental.

1. Introduction

The Riyadh Metro Project (RMP) is commissioned and supervised by Arriyadh Development Authority (ADA), the executive arm of the High Commission for the Development of Arriyadh. Currently the largest public works project in the world, RMP is located in Riyadh, Kingdom of Saudi Arabia, and involves the construction of the city’s first rapid transit network of surface busses and six lines (178km) of autonomous passenger light rail. The BACS consortium (consisting of Bechtel, Almabani, CCC, and Siemens) is constructing lines 1 and 2 of the project and has hired AECOM as the lead designer for several components of the project including the elevated viaducts and stations. The large magnitude and aggressive schedule of the project called for the mobilization of several AECOM offices around the world. This paper focuses on the design of precast segmental viaducts which were carried out in Boston, USA; Croydon, UK; Madrid, Spain; and Riyadh, KSA.

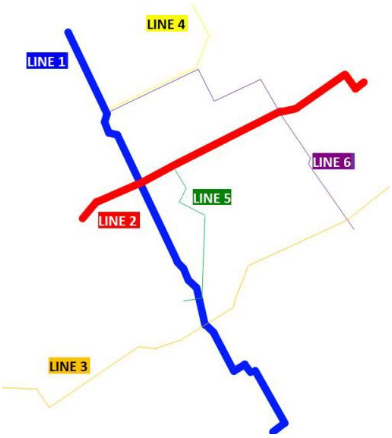

Figure 1. Riyadh Metro System Map.

2. Project description

Lines 1 (Blue) and 2 (Red) contain over 6000 precast concrete segments total over 21km of precast segmental viaducts, 11 elevated stations, 7 balanced cantilever (BC) bridges, and four 3-span continuous units, primarily carrying double, but also single, and triple tracks. The viaducts support direct fixation tracks with continuously welded rails throughout their entire length. Spans vary from 21m to 70m with curved radii as tight as 100m. The precast segments are designed to be cast using short line molds and match cast fabrication techniques. The method of erection is span-by-span using overhead gantries for the shorter spans, and balanced cantilever using a pair of lifting frames for the longer spans. The project has more than 600 piers of various types of cast-in-place concrete founded primarily on drilled shafts.

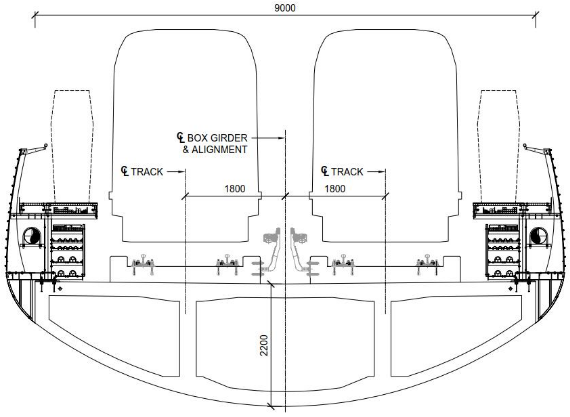

Figure 2 – Typical Viaduct Section

3. Design Criteria

The design of viaduct structures conforms to AASHTO LRFD 6th Ed., ACI-358.1R-92, and other relevant codes and design specifications. The design load combinations are defined by the most severe combinations of AASHTO and ACI-358 per the project requirement. A set of project specific 17 load combinations was created to satisfy the requirement.

The design Live Load (LL) is based on a maximum static axle load of 132.4kN, which is the same for all train axles:

- 2-Car Train: H=2.1m, C=9.9m, A=4.506m
- 4-Car Train: H=2.1m, C Outer bogies =9.9m, C

Inner bogies =10.222m and A=4.506m

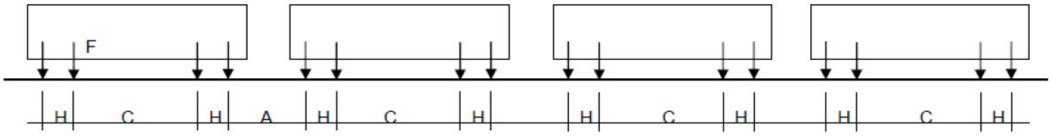

Figure 3 – Design Live Load Arrangement

The 50-year lowest and highest ambient temperatures in Riyadh are -5°C and +50°C, respectively. For the purpose of calculating track- structure interaction, the design temperature range for the rails is taken as -50°C to +40°C. The design temperature range in concrete deck is taken as -30°C to +30°C as specified in the KSA Highway Design Manual. The maximum allowable broken rail gap at the lowest design temperature is taken as 75mm per the diameter of the train wheel used on this project.

The seismic design conforms to AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2nd Ed. The seismic characteristics for this project in Riyadh fall in seismic design category (SDC) A, and a minimum seismic coefficient Cs of 0.06 per the project requirement governed the seismic loads.

The wind loads are based on a 3-second gust speed of 166 km/h for a 100-year return period per the project requirement. In general for transverse loads, wind loads governed for tangent alignment portions, and uniform temperature loads in rails governed for curved alignments.

The primary vertical natural frequencies of 28m to 38m simple spans are between 2.6Hz and 4.8Hz and *conform to EN1991-2.*

4. Superstructures types

4.1. Span-by-span (SBS) bridges.

The vast majority of viaduct spans are simply supported ranging in span length from 24m to 38m, both straight and curved. The segment width is 9m for straight spans, and widens to 9.75m in curves to accommodate the extra space required by train sweep through the tight curvature. The curved soffit is a unique feature of the viaducts and is one of the aesthetic features of the project. Post-tensioning tendons consist of a combination of internal and external strand tendons.

Elevated Station spans are shorter (21m) and made continuous for live and superimposed dead loads. The station spans are required to support the elevated station superstructure and canopy, requiring them to be cast with integral ‘wings’ for a total segment width of 16.7m. The extra width of the segments, as well as the large superimposed loads from the elevated station require these segments to be heavily reinforced and shortened to 2m long vs the 3.8m length for typical double track segments. A secondary placement of cast-in-place slabs on both sides complete the platform area.

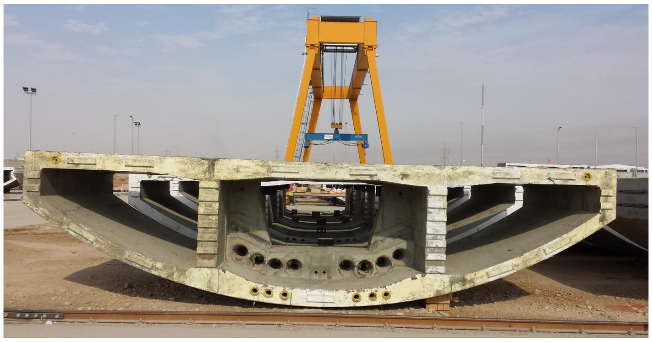

Figure 4 – Typical Double Track Segment with deviator for external tendons

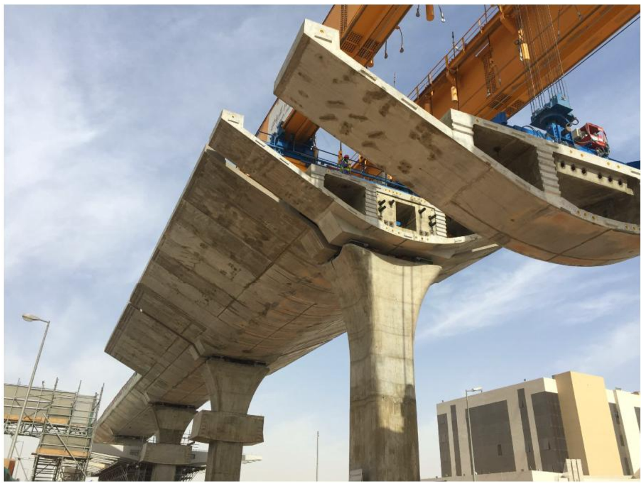

Figure 5 –Elevated Station construction

Due to site constraints, one of the elevated stations has platforms between tracks rather than on either side of the viaduct. To interface with this station, single and triple track spans were developed using the same cross sectional form as the double track segments with some variations.

Simple span bridge construction for straight and curved bridges is carried out using Launching Girders (LG). The LGs had to be designed to accommodate the span configurations in Table 1:

Radius	Span (m)	Deck width (m)
≥ 100	28	9.75
≥ 150	30	9.75
≥ 200	32	9.75
≥ 250	34	9.75
≥ 300	35	9.75
≥ 530	35 - 38	9.00

Table 1 – Span-by-Span Configurations

A typical LG used in the project is shown in Figure 6 and Figure 7. LG front and back supports are anchored to the top of piers using 57mm PT bars.

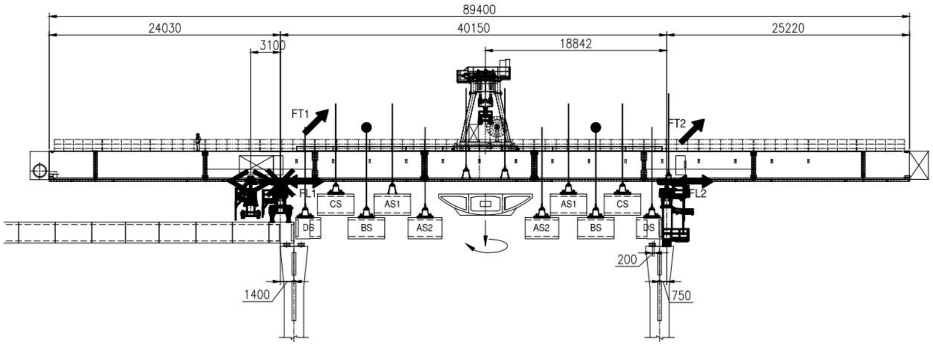

Figure 6 – Launching Gantry Configuration

Figure 7 – LG erecting SBS span

The overall length of the LG is 90m. During the erection of the span, the front leg is anchored to the ahead pier while the rear and auxiliary supports are positioned in the previously erected span as shown in Figure 6. The segments are typically delivered from the roadway median below but they can also be delivered from the previously erected span. Lifting hangers are then engaged and, segment weight is to the lifting hangers. Once all segments are positioned, they are epoxied together using a slow set epoxy and connected together using temporary PT bars.

For a typical 35m straight span, there are a total of 6-22 external and 4-15 internal tendons. Strand size is 15.2mm (0.6”). The stressing sequence is as follows: external tendons are stressed first and then hanging bars are disengaged, internal tendons are stressed next, temporary PT bars can then be removed and LG launched forward.

4.2. Balanced Cantilever Bridges.

A total of seven BC bridges have been introduced in line 1 & 2 wherever the construction of typical SBS structures was impractical. There are three BC bridges with radii as tight as 100m. The maximum span lengths for the straight and curved BC Bridges are 70m and 58m, respectively.

Additionally, there is special BCC that is placed into a station with a central span of 47m and cast in situ ribs for the platform and canopy.

Construction of BC Bridges in Riyadh Metro Project follows a typical balanced cantilever erection methodology. The pier segments are installed by crane on the piers, secured on the temporary bearings and tied down by 4 PT bars. Then, two adjacent segments are installed by crane on the temporary shoring towers. Moving Lifting Frames (MLFs) are installed to lift the remaining segments and install them on both sides of the cantilevers. The procedure of installing a segment includes: applying epoxy to the face of segment, connecting it to the previously installed segment by temporary PT bars and finally stressing the cantilever tendons once a pair of segments is in place.

After the cantilevers are completed, the cast in place (CIP) closures are poured in the main span first for the longer BC bridges and in the side spans first for the shorter BC bridges. To minimize the shrinkage effect in the fresh CIP concrete, 12 hours after placing the concrete the first two continuity tendons at top and bottom are stressed to 20% final force.

After stressing all continuity tendons, temporary PT bars are removed and the tendons are grouted. Placement of track slab concrete and installation of all wayside equipment, walkways and cladding is the final step to complete the BC bridges.

Figure 8 – BCC closure joint contruction

4.3. Bearings.

The elastomeric bearings are by far the most common, numbering approximately 1800 out of a total of about 2400 bearings for the entire viaduct.

Guided elastomeric bearings are used at the elevated stations to restrict the lateral movement of the spans, preventing damage to the station superstructure and mechanical systems

Pot bearings were used in areas of very high vertical or lateral reaction, or uplift. All balanced cantilever bridges are supported on Pot bearings to handle the very high vertical loads. Pot bearings are also used in tightly curved spans (radius ≤ 250m) to handle the very high TSI forces.

5. Substructures types

5.1. Geotecnical Characteristic.

The viaduct foundations are supported on competent rock, which is characterized by moderately to slightly weathered limestone rock, with a uniaxial compressive strength equal to or greater than 15 MPa. For soil-structure interaction analysis, a subgrade reaction value of 2740 MN/m3 in the rock was used. However, it was determined that cavities may be encountered occasionally.

5.2. Foundation types.

The piers are typically founded on 3m diameter drilled mono-shafts to minimize traffic disruptions and avoid conflicts with the existing utilities and roadway facilities. Spread footings are used where there are no utility or traffic maintenance conflicts or competent rock is present near the surface. The foundations with eccentric loads like C-piers are founded on either 4-shaft pile caps or spread footing foundations.

5.3. Piers types.

Given the large number of piers on the project, custom designs were deemed impractical. Instead, a limited number of standardized pier and foundation designs were prepared to cover the majority of locations. Referred to as “Typical Piers,” these designs were broken down by span, pier height, and curve radius, as shown in Table 2. For a given pier size, different reinforcement patterns are represented by the letter designation at the end of the pier type.

Type	Alignment	Max Pier height (m)	Span (m)	Size (m x m)
TP-1	SBS - Straight	19.00	38.00	2.00 x 2.20
TP-2	BCC - Straight	12.00	BCC	2.00 x 2.20
TP-3	BCC - Curve	12.00	BCC	2.80 x 3.00
TP-4	SBS – Curve R < 250 m	19.00	32.00	2.80 x 3.00
TP-5	SBS – Curve R ≥ 250 m	19.00	35.00	2.00 x 3.00

Table 2 – Summary of Pier Types and Sizes

One of the most salient features of the pier design is the pier shape. The shape with the smallest cross-section dimensions was proportioned such that it fits within the typical median. However to accommodate higher force demands due to longer spans, taller piers, and curved alignments, it was necessary to use larger sections. The new sections were developed to preserve the key architectural characteristics of the basic shape.

Figure 9 – Basic Pier Shape

5.4. Hammerhead straddle and C-piers.

Due to either site constraints (i.e. crossing over or near existing roadways) or structural requirements from the superstructure, three additional special pier types were developed. Straddle piers consist of solid concrete columns with a trapezoidal post-tensioned cross beam set between the columns. These are used where the alignment of the viaduct carries the track over existing roadways. The connection between the column and the cross beam consists of a pair of spirally-reinforced concrete "pins" monolithically cast with the column and cross beam that resist horizontal loads, yet permit rotation of the cross beam to prevent moment transfer into the columns.

C-piers consist of cast-in-place concrete columns with eccentric caps, both post-tensioned with PT bars. C-piers handle situations where the pier column is constrained by existing infrastructure, but the eccentricity between the center of the pier and the track is less than 3.5m.

Hammerhead pier are used to support single and triple tracks to prevent differential movements between the two tracks that otherwise may occur with a single pier column, to minimize traffic impact, and to provide for a more aesthetic finished structure.

The project has paid special attention to ensure architectural compatibility between the three special piers mentioned above and the Typical Piers. The image presented in Figure 10 clearly demonstrates this.

Figure 10 – Construcion of C-Pier & Straddle Piers

6. Track structure interaction analysis

The metro system runs on continuously welded rails that are directly fixed to the deck by rail fasteners that slip along the rails under various conditions with friction forces; this track-structure interaction (TSI) has been considered in the design of viaduct structural components.

At curves with horizontal track radii smaller than 250m, the transverse forces were beyond the capacities of the elastomeric bearings, and the lateral displacements were excessive and the elastomeric bearings were replaced with longitudinally guided bearings, which resolved the excessive displacement issue. The large transverse forces at the curves were designed to be resisted by larger piers and foundations. It should be noted that using transversely unrestrained bearings at one end of a span and restrained bearing(s) at the adjoining end of the next span at the same pier can create excessive transverse shear concentration in rails between the spans and should be avoided; the bearing articulation was arranged to avoid this situation throughout the viaducts.

To meet the demands of TSI forces and all the various loadings experienced by each span, three major types of bearings were used throughout the project: steel reinforced elastomeric bearings (11 subtypes), guided steel reinforced elastomeric bearings (2 subtypes), and high-load multi-rotational “Pot” bearings (30 subtypes).

7. Precast yard

The precast yard is located South of the city and the proposed metro lines. It is a complex facility intended to produce more than 6000 segments for the project. It also includes labor quarters for 12,000 employees including recreational areas and facilities, warehouses, a machine shop, storage for Siemens, two concrete batch plants and aggregate storage with wash area.

There are four production lines and each line has its own gantry crane. Lines 1 thru 3 have 80 ton capacity crane and line 4 has 100 ton capacity crane. Between the lanes 1-2 and 3-4 respectively there is a rail moving tower crane with capacity of 10 tons each (total of 2) to support the construction of the molds and rebar jigs. Additionally, there are 7 mobile cranes at any one time and 3-4 front loader forklifts.

The storage capacity for the casting yard is in excess of 2400 segments and certain segments can be double stacked.

8. Constructions sequences and current status

In order to meet the project's aggressive schedules, BACS commissioned DEAL to design and fabricate five nearly identical Launching Gantries (LG) for the construction of the span-by-span bridges, and two Moving Lifting Frames (MLF) for the construction of balanced cantilever bridges.

Standard gantry erection rate peak is 4 spans a week working in two shifts. Typically it achieves 3 spans a week on average.

As discussed before, the spans of the elevated stations are also erected using the LG's, this allows for an uninterrupted movement of the LG's. Construction schedule of the balanced cantilever bridges using MLF's is generally independent of the span-by-span construction however closely coordinated to ensure no delays.

The viaducts are anticipated to be substantially completed by June 2017.

9. Conclusions

As expected, precast concrete segmental construction using a combination of span-by-span and balanced cantilever construction methods is proving to be very effective to construct 660 spans over live traffic and in a fairly congested urban setting and to overcome many site and logistic constraints.

Close collaboration among all parties listed below was necessary to fulfill ADA's vision of creating a world class, durable, aesthetically pleasing, and highly functional metro system in a short period of time.

Acknowledgments

Designers: AECOM offices of Boston, Croydon, Madrid, and Riyadh

BACS consortium: Bechtel, Almabani, CCC, and Siemens

Arriyadh Development Authority (ADA)

Riyadh Metro Transit Consultant (RMTC - Parsons, Egis, Systra)

Construction Engineering: McNary-Bergeron & Associates

Shop Drawings: Substructure: AECOM; Superstructure: Corven Engineering

Erection Equip. and Forms: DEAL / Post-Tensioning Supplier: Dywidag-Systems