DESIGN AND CONSTRUCTION OF THE VANCOUVER SKYTRAIN MILLENIUM LINE GUIDEWAY

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Abstract

SAR Transit, a joint venture of AMEC (formerly Agra Monenco) and Aecon Infrastructure (formerly SC Infrastructure), completed construction of their 15.6-kilometer portion of elevated guideway of the Skytrain Millennium Line in Vancouver, British Columbia, under a design-build contract, less than two years after Notice of Award. This is an astonishing accomplishment in a built-up urban environment with access, permitting and traffic-management issues. This paper focuses on the design and construction features that made this achievement possible.

Precast segmental technology was employed to meet the schedule requirements. Casting 5,675 segments was accomplished in 14 months. Erection started in March 2000 and the last segment of the 485 spans was erected in February 2001. Substantial contract performance was achieved in May 2001.

The project consists mainly of 37-meter simple spans supporting two light rail tracks. There are also sections where single-track box girders and combined boxes are necessary. At the nine stations along the line, the guideway substructure provides support for platform and roof structures as well. There are also seven long-span structures erected in balanced cantilever.

Implementation of a single construction system to address the varying project requirements, and a few noteworthy innovations, were key to the success of the project.

1. Introduction

The Skytrain Millennium Line Project is a 20.4-km extension of the Automated Light Rail Transit System that was established in Vancouver, British Columbia in the early 1980's. This paper describes the 15.6-km elevated portion of that project that was built under a fast-track design-build contract by SAR Transit JV. With 5,675 segments, it is currently the largest segmental project built in North America.

The design of the project started at contract award in May 1999. Construction activities commenced in October of the same year, and the last span was erected in February 2001.

The standard two-track guideway structure is a 37-meter-long simply supported concrete box girder on octagonal piers with flared capitals. The typical foundation element is a large-diameter single shaft. In addition to the typical configuration, there are separated sections with single-track box girders; pocket tracks, and crossovers where the typical box girder must be augmented to achieve the required width; stations, where the structure depth must be reduced and the substructure must carry platform and roof loads; and medium-to-long-span structures where greater section depth and alternate erection methods are required.

2. Structural System

Precast segmental technology was used throughout for all of these structures. Implementation of a single construction system to address the varying project requirements was one of the main keys to the success of the project. In particular, the use of segmental techniques enabled SAR Transit to incorporate the seven medium-to-long-span bridges into their contract. Originally, the Owner intended to let these "special structures" as seven design-bid-build contracts. The continuous erection operations afforded by this change eliminated seven additional interface concerns for the owner. They were also a great schedule advantage, as the need to demobilize the erection trusses at the special structures and re-locate them was eliminated.

Segmental construction also allowed SAR to keep the size of the precast elements small, such that they constituted a "legal load" and did not require special permits to be transported. Segments could be delivered during daylight hours except for minor exclusions for peak traffic periods. Moreover, the overhead erection equipment did not interfere with traffic and could generally be operated and advanced during daylight hours.

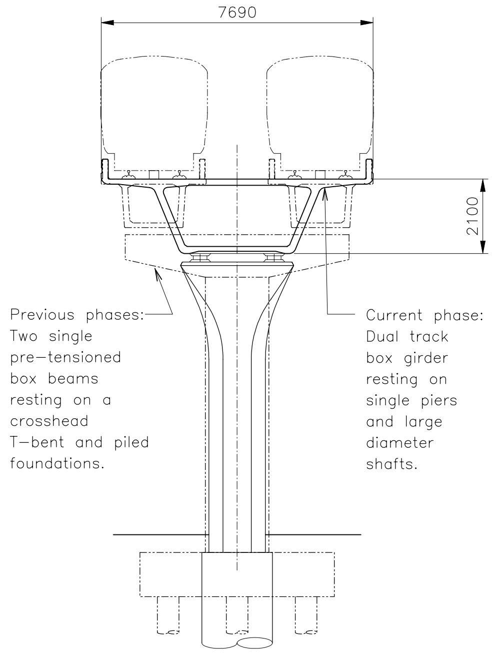
By developing a minimum number of standard cross sections and segment types, and eliminating almost all cast-in-place concrete work, most of the effort could be concentrated in the casting yard, and erection operations could be kept as efficient and non-invasive as possible.

The 15.6 km of SAR's elevated guideway contract is comprised of 4 distinct types of segments:

- Typical dual-track segments are 2.1 m deep and 7.69 m wide and varied from 2.45 to 3.2 meters in length. Segment weights ranged from 22 to 32 tonnes.
- Single-track segments are also 2.1m deep and are used in a center platform station and where the track centers diverge to greater than the typical 4.7-meter separation.
- Station segments are similar to the typical dual-track segments, but are only 1.6 meters deep.
- Long span segments have vertical webs and vary in depth from 2.1m to 4.5m. The two longest span structures, with main spans of 83 and 90m, utilize the deep 4.5-meter-deep segments, while the remaining 5 structures all use the 3.5-meter maximum-depth segments. The length of these segments varies from 2.3 to 2.75m.

Typical Dual Track Guideway

Figure 1: Typical Guideway



Because of the challenging contract schedule, construction speed was the paramount consideration in the design of the typical guideway, which comprised the majority of the work. In this context, a large-diameter single drilled shaft was chosen as the basic foundation element where the depth to competent material precluded the use of spread footings or where utility relocation, railroad interface and traffic control issues made large plan-area excavations difficult. Although the drilled-shaft foundations were relatively flexible horizontally, they exhibited good seismic resistance. At some locations, installation was prolonged due to the ubiquitous boulders in the glacial till that underlays much of the alignment.

Without impediments from boulders, the complete single-shaft foundation could easily be accomplished in one day, including boring operations, rebar fixing and concrete placement. The pier site was then ready for column construction the next day.

The typical column comprised an octagonal stem and a “tulip”-shaped capital. The capital was designed to be aesthetically pleasing, with the slope of the box-girder webs repeated in the capital, followed by a gentle transition curve into the stem. The shape was also structurally efficient and minimized the reinforcement required for the pier cap. More importantly for SAR, this design allowed all the reinforcement to be fixed in the form at one time, and the form for the capital then served as a large funnel to aid in placing the concrete. This allowed for construction of the pier in a single day, including erection of the form, reinforcement fixing, and concrete placement.

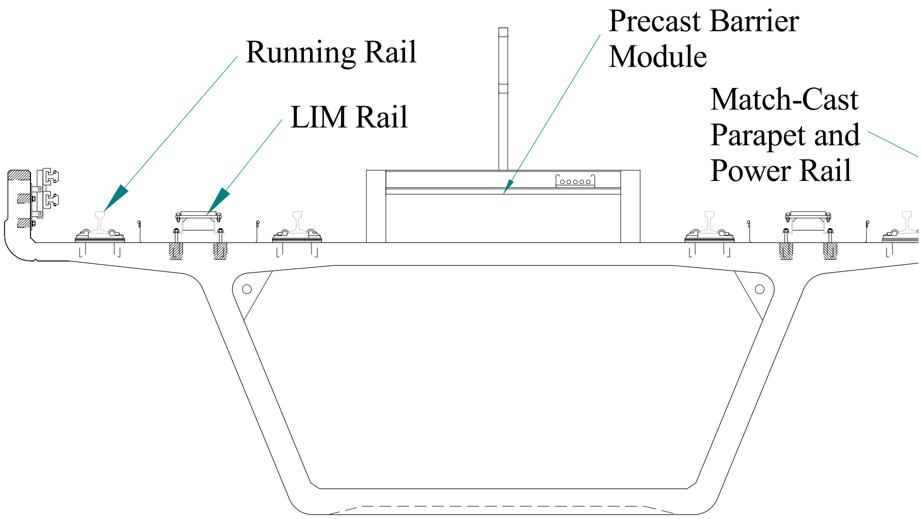
Superstructure erection was accomplished by means of the span-by-span method and was based on a one-day erection cycle. The box girders were designed as simple spans, so that a complete span would obtain after stressing the longitudinal prestressing, without requirement for any cast-in-place concrete work in order to achieve continuity. The external tendons were prefabricated on the deck of the previous span and pulled into place. Tendon harping was accomplished with 3D saddles, called “diabolos”, that were cast into deviator beams inside the box. With the diabolos, the tendon could be deviated in any direction through any required angle so that they are standard for every span; it is not necessary to align them in the form to account for changes in span length, or for horizontal and vertical curves.

In order to eliminate as much cast-in-situ concrete as possible, the parapets were precast. The outer parapet was cast as part of the segments and was included as part of the match-cast joint. This resulted in superior quality of the parapets, which did not have the vertical cracking due to dissimilar shrinkage normally associated with those elements. SAR then devised inner parapets that were precast separately and joined to the guideway after the segments were erected. They comprised two barrier walls 3200mm long spaced at 2000mm transversely which were connected by three crosswalls to make an “egg-crate” module. These modules were laid end to end along the guideway to create the two inner barriers and the emergency walkway between them. In this way, the inner parapet was composed of stable self-supporting elements that had only to be made fast to the deck of the guideway by means of six double-headed dowels.

Substantial concrete shear keys were cast on top of the columns. By interlocking with corbels extending from the pier segments, these keys provided a positive transverse anchor to hold the girders in place on top of the piers during an earthquake. Since the keys were cast tightly against bearing material on the pier segments after the spans were aligned, they were also used to resist the transverse forces arising from rail structure interactions. This dual use allowed SAR to support the superstructure on elastomeric bearings, which reduced cost and saved time on the erection schedule.

Perhaps the greatest benefit to finishing the guideway quickly after the span erection was complete was the method of casting the inserts for the rail fasteners directly into the deck of the superstructure. With the typical use of direct fixation, rail fasteners are secured on plinths made as secondary pours to allow for adjustments in elevation and alignment so that the tight placement tolerances for running rails can be achieved. As part of previous phases of Skytrain, BC Transit had developed the technique of casting inserts for running-rail fasteners directly into the structural slab of the full-span precast beams, so that the rail plinth would not longer be needed. SAR Transit extended its applicability to precast-segmental construction, wherein the placement tolerances had to be maintained across segment joints that offered no opportunity for readjustment after erection. SAR developed special jigs mounted on the casting machines to rigidly hold the inserts and allow precise surveys to be made. Segments were then cast, following normal short line procedures. After some initial debugging, the system developed by SAR proved to be extremely effective and was one of the primary factors in bringing the project into operation quickly.

Figure 2: Direct Fixation of Rails



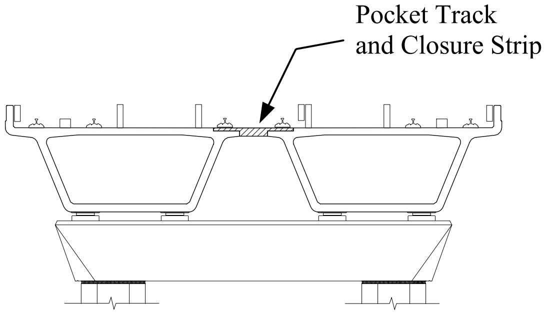
Pocket Tracks

At several locations in the project, pocket tracks were required for train storage. These installations required additional superstructure width in order to accommodate the third track, and also required special measures to anchor the switches and associated train-control hardware.

In order to provide the required width within the framework of the standard superstructure elements, pocket tracks were made up from multiple box girders placed side by side. SAR Transit used a side-shifting truss in these areas that permitted them to easily slide the truss from one box-girder centerline to the other and therefore place both box girders from one support position. Continuity between deck slabs was achieved with a secondary pour placed between the girders after final alignment.

The elevation of the top slab was depressed slightly in the pocket-track areas to allow for a cast-in-place second pour that was provided to anchor the special trackwork elements. Since the switches in the tracks required breaks in the running rails, the continuous rail forces had to be transferred to the superstructure with rail anchors. Where this condition occurred near a pier, continuity in the superstructure was required also. Rather than change the structural system by constructing continuous spans, "link slabs" were provided between adjacent spans to transfer these forces. The elements were designed to work primarily as axial members, and to "absorb" the rotations from live loads, temperature loads, etc.

Figure 3: Pocket Track Configuration



Stations

Nine stations were required within SAR Transit's contract. The civil portion of these stations consisted of the guideway beam supported on portal frames spaced at 20m centers. A special 1.6-meter-deep segment was developed to meet the architectural clearance and access requirements for these structures that were intended to have retail space and other ancillary uses. In order to avoid developing another type of pier segment, the superstructure in the station was made monolithic with the straddle beam of the portal frames.

The portal frames were designed to support the station platforms and roofs, making them, in effect, foundations for significant building structures. An effort was made to standardize the configuration of the portal frames at seven of the nine stations while permitting architectural license for unique stations that would reflect the character of their individual neighborhoods.

Special Structures

There were seven structures at various points within the alignment that were identified as "special" structures because of their greater span requirements. Originally the Owner had envisioned that these structures would be let in separate contracts, and it was expected that they would be constructed in steel. In order to avoid gaps in their portion, and the attendant inefficiencies involved with coordinating construction around them, SAR Transit proposed to the Owner that these structures be included in their contract. The Owner saw the advantages of this proposal and accepted.

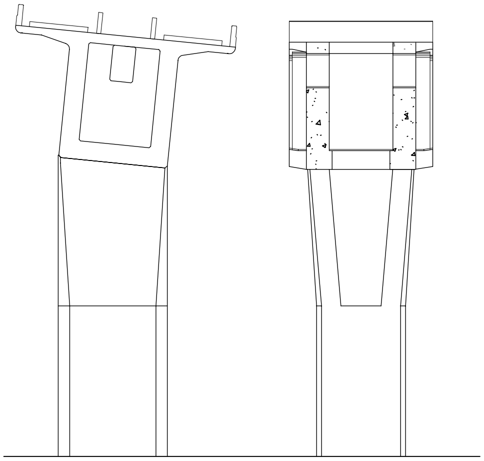


Figure 4: Balanced Cantilever Pier Segment

In order to be successful with these additional structures, SAR Transit had to design them to be constructed with the same equipment that would be used for the typical guideway structure. Precast segmental construction, in conjunction with the balanced-cantilever erection method, allowed them to use the same casting yard and other infrastructure to manufacture the bridge components. For erection of the balanced cantilever segments, a special "combi" truss was used. This truss was equipped with the trolley and other equipment required for balanced cantilever construction and also had the hangers and strength in bending to support an entire typical span, as required for span-by-span erection, allowing SAR to use if for both the typical and "special" structures.

For these bridges, a traditional segmental superstructure with internal tendons and vertical webs was employed. Main spans varied from 60 to 90 meters, with the 90-meter span being on a 275-meter horizontal curve. The 90-meter span and tight horizontal curve dictated pier segments monolithic with the piers. In balanced cantilever construction, casting the pier segments in place and then starting balanced-cantilever erection with a wet joint at the pier is the most often used method to make monolithic connections. SAR could not afford the time on the erection schedule to perform these operations, so they opted instead for a pier-segment design based on a precast shell with the diaphragms cast inside after the segment was erected. This design not only allowed them to precast the pier segment in the yard, but also permitted them to match-cast the starter segment. Only the diaphragms had to be cast in place. The precast shell served as formwork for the outer surface, and a simple wall form for the inner surfaces was all that was required in addition.

At the transition between the sloped webs of the typical spans and the vertical webs of the balanced cantilever structures, special attention was required to avoid a large unsightly discontinuity between the two. A pier segment with radically warped webs was developed as part of the balanced cantilever structure to make the transition gracefully within the length of one segment. Although the special form was an added expense, it resulted in a significant improvement in the aesthetics of the special structures, and eliminated the screen walls that would have otherwise been required.

The original design was for twin wall piers with vertical walls spaced at three meters. An improvement in the aesthetics was later implemented wherein the walls were sloped until they converged at a common solid stem. This design had a smaller footprint, which had horizontal clearance advantages in some critical high traffic locations. It also provided an architectural look that was more sympathetic to the stem-and-tulip pier of the typical guideway. Although it was not as efficient structurally, the appearance of the final product justified the additional cost.

Conclusion

For their portion of the Millennium Line, SAR Transit completed 15.6 kilometers of elevated guidway in two years. The first precast segment was produced four-and-one-half months after breaking ground for the casting yard; full production of 140 segments per week was achieved three months later. 5,675 segments were erected in eleven-and-a-half months, for a rate of 1.35 kilometers per month. The result is a high quality, aesthetically pleasing product that was delivered on time at a cost significantly lower than that of similar projects. The project is an excellent example of how design-build project delivery and segmental construction provide the means and flexibility to construct large transportation projects in difficult urban environments.

Figure5: Typical Span Erection with “Combi” Truss