SINGLE STEEL BOX GIRDER BRIDGES FOR THE TERMINAL DEVELOPMENT PROJECT AT TORONTO PEARSON INTERNATIONAL AIRPORT

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Abstract

This paper describes the bridge type selection process, preliminary and detailed design procedures, unique structural details and construction and steel erection for four complex curved single steel box girder bridges completed within the groundside component of the Terminal Development Project at Toronto Pearson International Airport for the Greater Toronto Airports Authority. The $4.4 billion project is scheduled for completion in three phases over a span of ten years, making it the largest single airport redevelopment project undertaken in Canada.

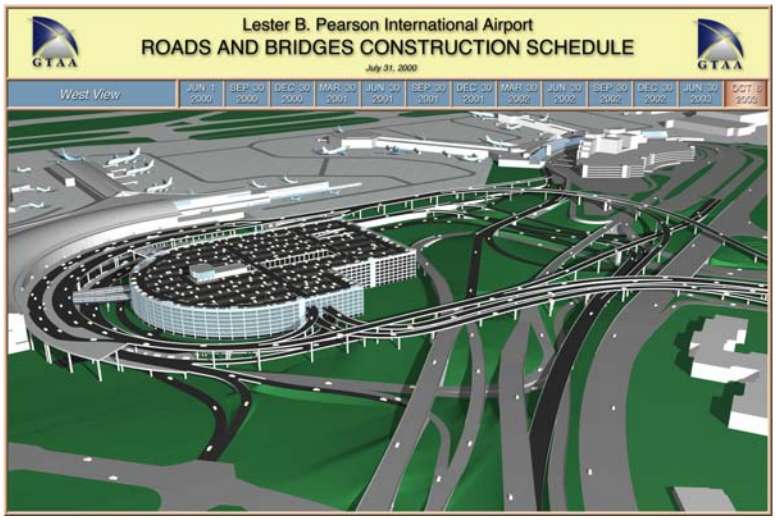
The composite single steel box girder/concrete deck bridges are not commonly constructed in Canada. On this project, they were implemented for the single lane, high-speed ramps connecting the existing Highway system with the approach roads to the New Terminal One building. The single steel box girder bridge type was adopted as the optimal solution compared to other structure types, for specific locations. The governing criteria for type selection were complex geometry and deck width, feasibility, the need to maintain traffic under the bridges throughout construction, and limited space under the bridges to provide falsework supports.

The number of spans varies between four and nine with the maximum spans up to 56 meters in length. Total length of bridges varies between 164 and 371 meters. Road geometry constraints resulted in minimum horizontal curve radius of 148.5 meters and maximum 6% grades. The unique details used in these bridges present an alternative, cost-effective approach in meeting each of the Client's needs using innovative detailing and appropriate construction technology. The structures were tendered approximately 15% below the engineer's estimates. The four bridges were completed in two construction contracts, between 2001 and 2003.

Introduction

Toronto Pearson International Airport (TPIA) is Canada's busiest airport, serving as a major hub for both international and domestic flights to and from central Canada. The $4.4 billion Terminal Development Project is scheduled for completion in three phases over a span of ten years, making it the largest single airport redevelopment project undertaken in Canada. The first phase of the project – New Terminal One and the surrounding groundside infrastructure is now fully operational and open to the public. These improvements have enabled the Owner, the Greater Toronto Airports Authority (GTAA) to expand the airport and accommodate increasing demands for air travel.

Redevelopment of the airport terminals involves replacing existing Terminals 1 and 2 with a single facility. This is the preferred alternative for addressing the long-term needs for terminal capacity. The overall development of the airport includes a substantial rebuilding of the access roadway network to facilitate the operation of the new terminal, and the relocation of many airport support functions. All construction is executed while maintaining full traffic operations in and around the airport.



In 1997, UMA Engineering Ltd. (UMA), in joint venture with DMJM+Harris, Inc. was awarded the Lead Engineer role for the redevelopment of the groundside component of the Terminal Development Project. The UMA / DMJM+Harris joint venture is known as the Greater Toronto Airport Groundside Association (GTAGA).

GTAGA was responsible to the GTAA for all groundside facilities and infrastructure, including the new 342,000 m^2 parking garage for 12,600 vehicles, over 80 lane kms of roads and 95,000 m^2 of elevated structure on 64 bridges, and extensive relocation and provision of utilities related to and affected by the groundside work.

Project Inventory	
Roads Lane Kilometres	80
Structures Lane Kilometres	20
Number of Bridges	64
Kilometres of Storm Drainage Pipes	15
Kilometres Water and Fire Mains	4

This phase of the project including the complete road network and parking garage was completed in autumn, 2003.

THE CHALLENGE

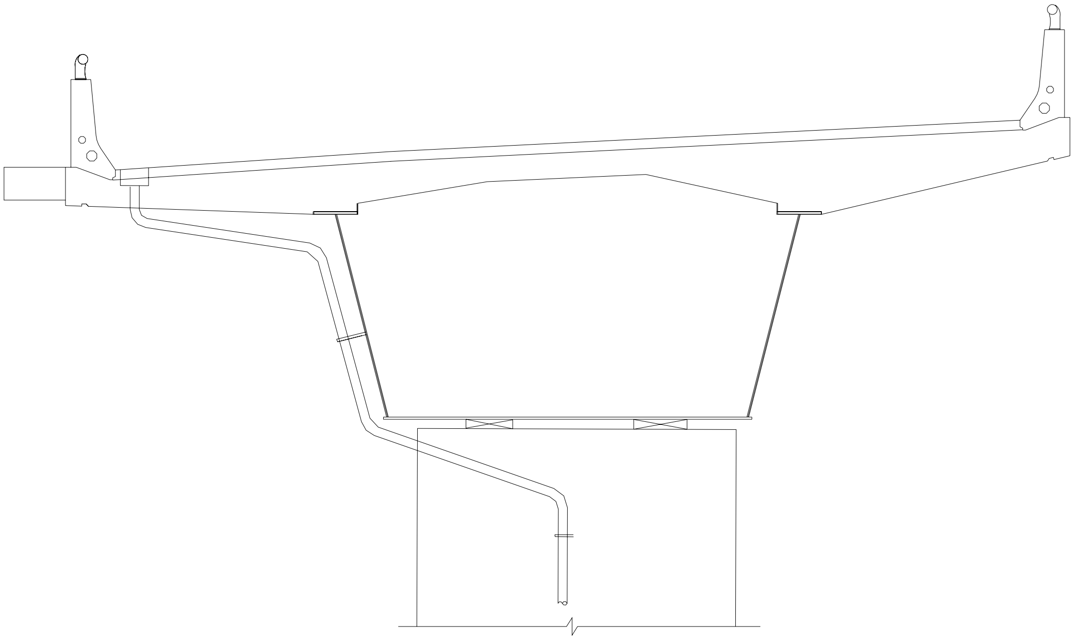
During preliminary design, all new bridges were planned to be post tensioned concrete deck type structures, with various span lengths and span arrangements, to ensure a uniform appearance at the entire airport site.

At this time, information about existing and new underground utilities, the full extent of new roadways, clearances for the planned People Mover and light Rail Link and schedule of construction contracts were not available. All of this information was collected at the start of the detailed design. It presented constraints that governed the bridge design. It was noted that specific areas at the ground site, where some of the new bridges were to be constructed, had severe "congestion" of roadways, utilities and overlapping construction contracts.

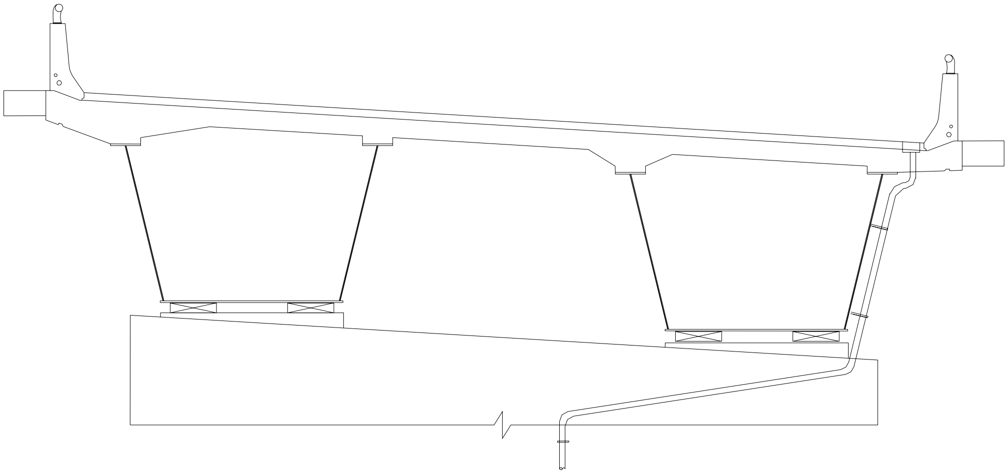
The challenge during detailed design was to select a structure type that would reduce congestion problems in these areas, and have the design and contract documents completed within the given schedule and budget. The bridge design consultant had to meet the following Owner's requirements:

- Minimize GTAA capital costs;
- Meet all geometry design criteria, namely:
    - Alignments with tight horizontal curve (minimum radius 148.5 m). As a result, the issue of ensuring the stability against overturning of the bridge had to be addressed during the design.
    - Complex vertical profiles with maximum grades up to 6 % combined with tight vertical curves within the structures.
    - Relatively narrow deck width of 9.16 m which is typical for single lane ramp structures.
    - End diaphragm under a 45 degree skew, to join to the existing bridge with skewed geometry. The constructability of this area had to be reviewed during the bridge type selection.
    - Fitting the new structure on a previously constructed pier, designed to accommodate a shallow concrete deck bridge. The required reduction in overall depth of the superstructure in the end span had to be considered during design to account for reduced load capacity of this section.
- Maintain traffic on all existing roads under and around the bridges during construction.
- Minimize impact on GTAA operations and other stakeholders by positioning the bridge piers clear of existing roads and underground utilities.
- Facilitate construction to accommodate existing and new traffic routes, including temporary construction traffic and numerous adjacent Terminal Development Project sites/contracts.

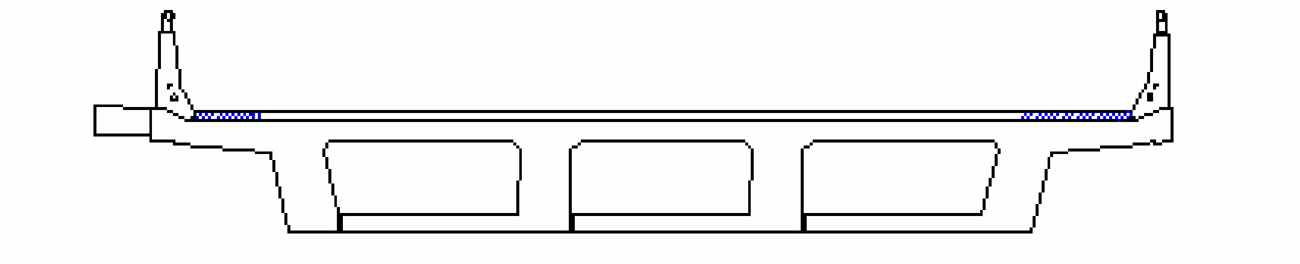
UMA completed a feasibility study that included a comparative cost analysis to determine the most economical and aesthetically pleasing structure type. Three structural options were analyzed; post-tensioned concrete voided deck, multi-box steel girder and single steel box girder type. The feasibility analysis indicated that the cost of the steel girder bridge type is 10% to 20% lower than the post tensioned concrete bridge type.



Single Steel Box Girder



Multiple Steel Box Girder



Post Tensioned Concrete Deck Voided

THE SOLUTION

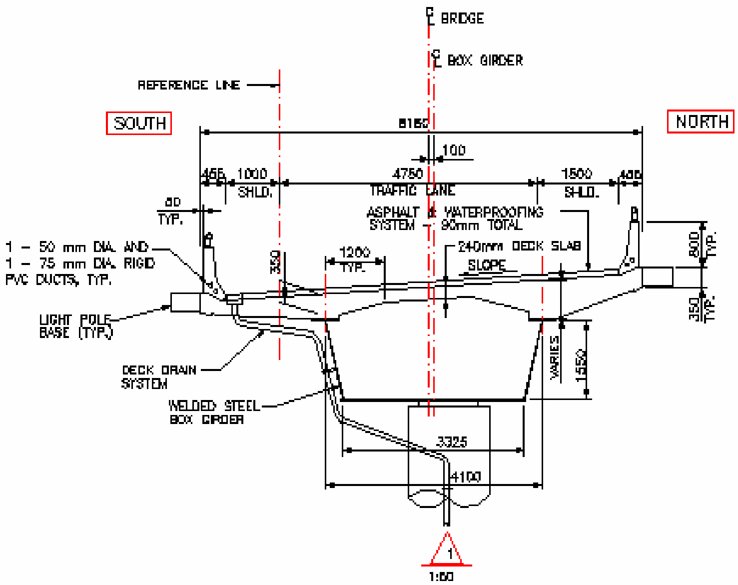
The use of the girder type of structure for the bridges in congested areas eliminated the need for elaborate falsework, typically required for the cast-in-place concrete structures; thus reducing adverse traffic impacts. Also, the construction could be completed in smaller work zones. However, the use of concrete precast girders was not an option due to the curved alignments and complex profiles of the bridges. The application of steel box girders could reduce the on-site construction time, by maximizing the erection lifts.

Once the box girder section type was approved by the GTAA, four bridge sites were identified as suitable locations for implementation of the single steel box girder structures. The governing criterion for the use of single box girders on these sites was the relatively narrow (9.21m) deck of the bridge. These bridges are located close to the existing major roads, including Highway 427 and Airport Road, and are numbered Bridge 205, 311, 604 and 605.

All four bridges are carrying one 4.75m traffic lane with 2.5m and 1.0m wide shoulders. The design speeds vary between 60km/h and 90km/h.

During the analysis of the sites, at least one end bridge span was positioned clear of existing roads underneath, to ensure the construcability of the bridges. It was anticipated that a temporary shoring tower would be required to start the erection of the bridge at one end span.

The single box section was used to achieve the most economical structural arrangement. The unique features of this section are:



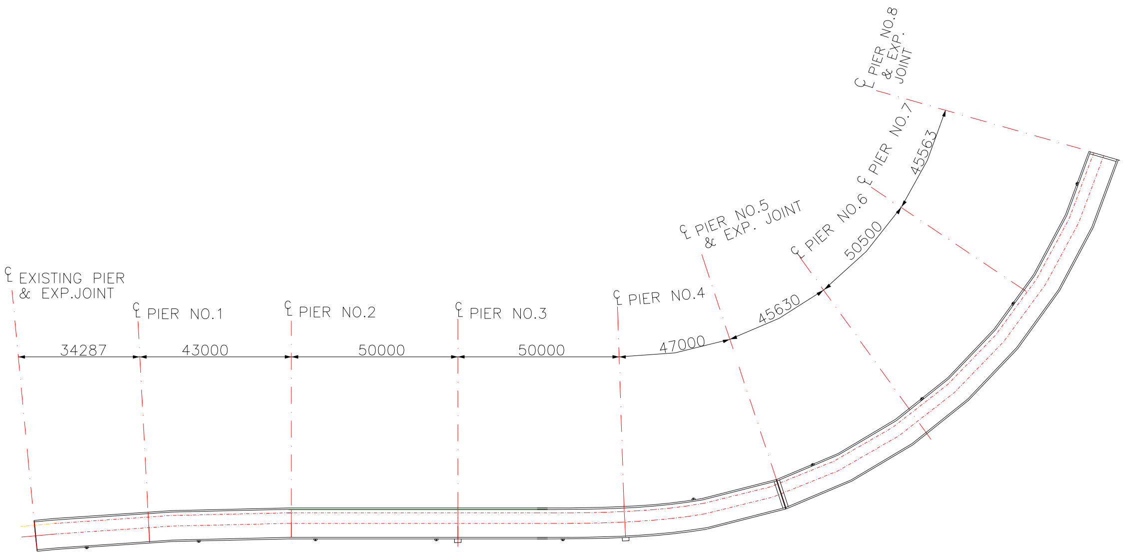
Detailed Cross Section

- The deck cantilever is at the maximum length for reinforced concrete decks. The usual length of the deck cantilevers does not exceed 2.0 m. The required cantilever length for these bridges was 2.5 m.
- The size and shape of the steel box is larger and more complex than what is usually used in multi-girder type bridges. The common design principle is to leave the same number of boxes as the number of traffic lanes on the bridge. As a result, the tributary deck width is 4.0 m to 5.5 m and the boxes are 2000 to 3000 mm wide. For these bridges, the tributary area of the deck was 9.21 m (full deck width) and the boxes were 4210 mm wide.

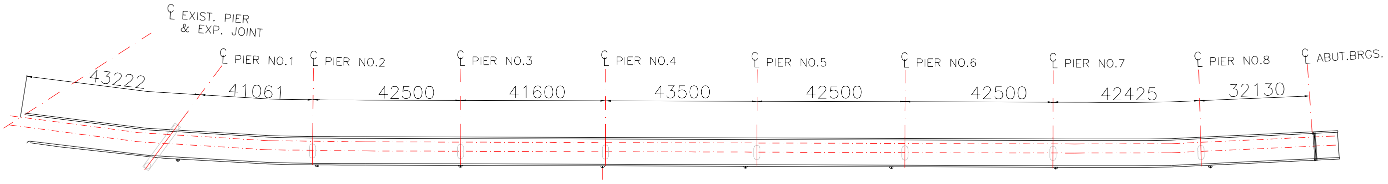
The Design

The final geometry of the bridges and the pier layout were governed by the available space to construct the piers and resulted in the following span arrangements:

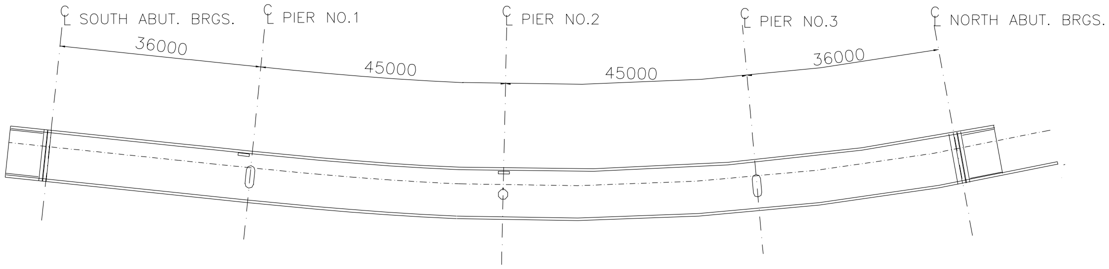
Bridge	Span Arrangement	Deck Area (m^2)	Metric Tonnes of Structural Steel
Bridge 205, Highway 427 to Departure Level	34+43+50+50+47+45.6+50.5+45.5 Total: 366 meters	3,360	760
Bridge 311, Departure Level to Airport Road	43.2+41+42.5+41.6+43.5+42.5+42.5+42.4+32.1 Total: 371 meters	3,030	654
Bridge 604, Core Roads	36+45+45+36 Total: 162 meters	1,485	294
Bridge 605, Core Roads	40+50+56+40 Total: 186 meters	1,705	345



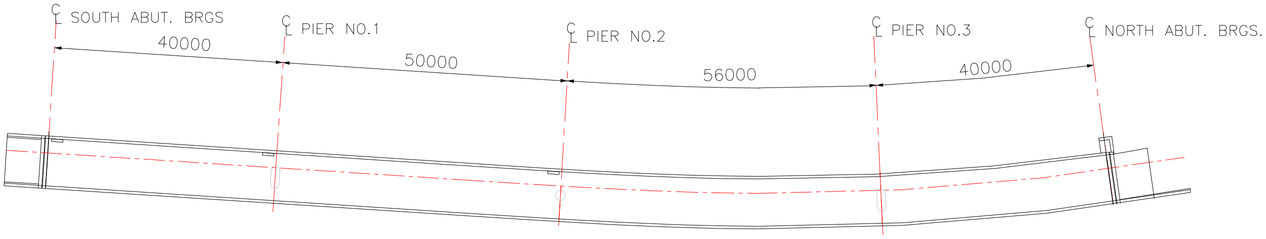
Bridge 205



Bridge 311



Bridge 604



Bridge 605

Compared to the preliminary design, the span arrangement and span lengths were modified for Bridges 604 and 605 resulting in fewer but longer spans to cross the widened Highway 409. The congested road network under the bridges prevented the construction of the “hammer head” type of pier at the middle pier of these bridges. Therefore they were designed as a single pier with a single bearing.

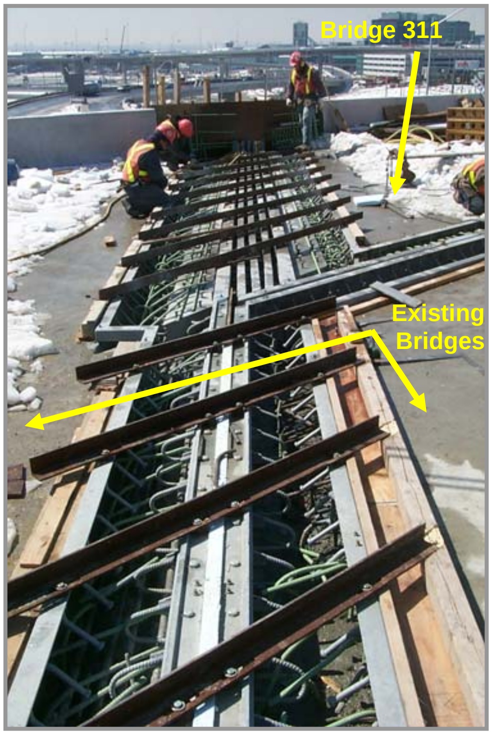
Existing utilities such as fibre optic cables, and existing roadways governed the design of some piers for Bridges 205 and 311. The concrete portal frame was constructed at Pier 1 of the Bridge 311, to support the steel superstructure over the existing roadway. The double column and column cap arrangements were used to span over the buried utility ducts for Piers 3 and 4 of Bridge 205.

Single Pier with single bearing

Piers 3 and 4 of Bridge 205

Pier 1 of Bridge 311

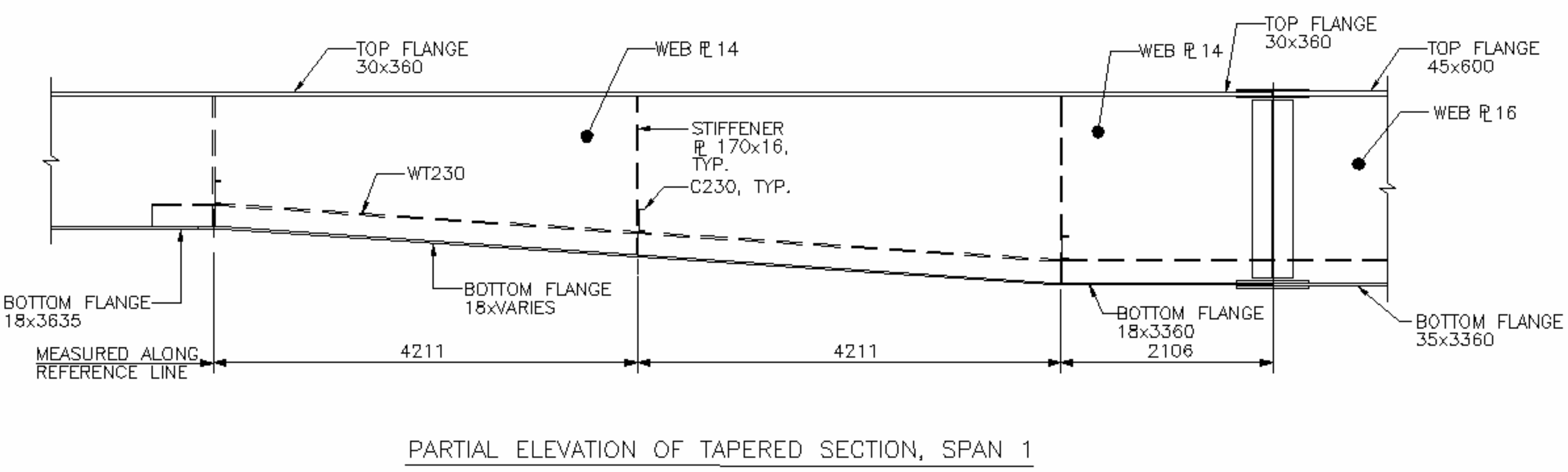
The last three spans of Bridge 205 were in a 148 m radius horizontal curve, while the rest of the bridge was in a slight "S" curve. To control large movements of the structure due to temperature change, and to improve the stability against overturning, an additional expansion joint was designed and constructed at Pier 5, splitting the bridge into two independent structures. Effectively, one structure behaved as a straight structure while the curved part had to be analysed for overturning effects.



Expansion joint of Bridge 311

The connection of Bridge 311 to two existing post-tensioned concrete bridges was done under a 45 degree skew. The end diaphragm and the expansion joints were designed to withstand all forces and accommodate larger movements that occur at this connection. At this location, 3 different types of expansion joints had to be constructed together; a large movement modular joint and a transverse joint between Bridge 311 and existing bridges; and a "Type A" strip seal expansion joint between existing bridges.

At the previously constructed pier of Bridge 205, the height of the steel box was reduced to 1,300mm in order to fit the structure into predefined geometrical constraints. The design of the steel box in span 1 allowed for gradual height change, through a taper of webs and bottom flange, while maintaining the overall top flange spacing.



Taper of steel box at Bridge 205

During the preliminary superstructure design, OMBAS bridge design software was used to determine typical bridge cross sections. The concrete deck was 9.21m wide, with 2.5m long deck cantilivers. The steel box was 1,850mm deep and 4,210mm wide. The steel plate thickness for the top and bottom flanges varied between 18mm and 60mm, and between 14mm and 18mm for the webs. During the design, the 2.5m long deck cantilever was considered to be post tensioned, however the analysis confirmed that the 350mm thick reinforced concrete cantilever was structurally acceptable.

The detailed design and analysis of the 4 bridges was completed using two independent full three-dimensional finite element models. In the first model, the steel box was approximated with plate finite elements, and the deck was approximated with the orthogonal grillage. The plate element mesh was made denser at the supports to accurately calculate the forces at the diaphragms. In the second model, for the independent design check, the steel box and the concrete deck were modelled with member elements. The horizontal cross bracing, that is typically designed for support during erection only, was incorporated as an integral part of the cross section to ensure the stability of the steel box. The section properties of the box for the second model were calculated with replacement of the cross bracing with the equal plate thickness. The equal plate thickness was determined on the assumption of equal horizontal movement/distortion of the top of the box.

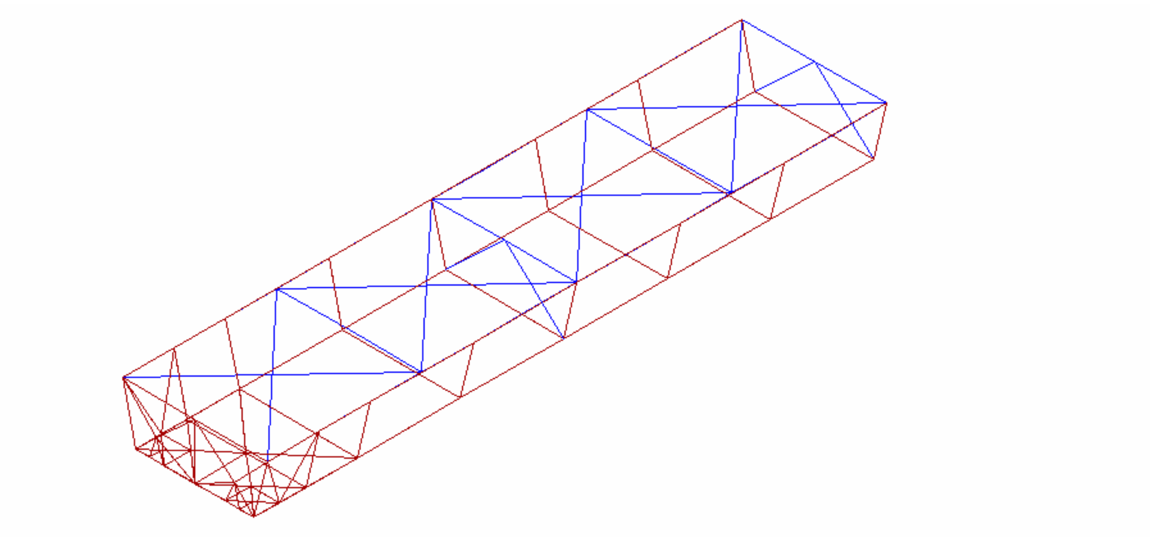


Plate element model of a steel box girder

Ensuring the stability of the structures was a major design challenge. Due to the geometry of the structures and the load configurations, both load induced torsion and self (geometry) induced torsion were present. They ultimately resulted in uplift of the supports. The uplift of bearings was higher at the bridges with smaller horizontal alignment curves. The implemented solutions were to specify the bearings with the uplift restrainers; and to design the wide diaphragms at the end supports to spread the bearings and reduce or eliminate the uplift forces.

Wide diaphragm at Bridge 205

The Construction

The structures were manufactured using atmospheric corrosion resistant steel, grade 350A and 350AT for primary tension members. The total weight of four steel structures was in the order of 2050 metric tons. To ensure the timely supply of steel plates, the Owner approached the steel rolling mills in advance of the project to reserve the required steel quantities/rolling time.

Falsework for deck cantilever

Fabricating the girders with both horizontal and vertical curves required three dimensional modelling for the purpose of generating steel shop drawings. This ensured that the plate shapes and cuts were correct before the girder was assembled.

To facilitate the erection and transportation of the structure, each bridge span was divided into two segments. These segments, up to 31m in length, were manufactured and shipped to the site independently.

Deck construction of Bridge 604

During the erection, two segments in each span were joined on the ground, before being lifted onto the bridge piers. The construction of long deck cantilivers utilized special falsework system supported off the box girders only.

LESSONS LEARNED

Traditionally, bridges with complex geometry such as the four bridges described in this paper would be built as a post tensioned voided deck type of structure. During the construction of this type of bridge a falsework support structure is required along the entire length of the bridge.

When constructing a bridge in "green field", the time required to erect the temporary support structure (falsework), pour and cure the deck concrete and complete the post tensioning, prior to removing the temporary structure, does not pose many potential issues.

However, traffic maintenance during construction of the bridges in the congested areas of TPIA would become a logistic nightmare and was not feasible.

The presented structures prove that the use of steel box girders for the complex applications with limited construction areas is not only possible, but also feasible compared to the traditional approach.

The advantages of the steel box girder structures for this specific project, within the given space and time constraints can be summarized as:

- *Feasibility of the steel box girder bridge compared to other bridge types.* The cost comparison between different structure types, applicable for this project, indicated a 10% to 20% lower cost of the steel box girders than the post tensioned concrete. The actual tender prices were 15% lower than the estimates completed during the cost comparison.
- *Minimal disruption to existing airport operations, other construction contracts and surrounding roads during construction.* Spans located over live traffic were typically erected at night, during a four to six hour traffic closure. These closures were favoured by the Owner, because there are minimal airport activities between midnight and early morning. Temporary detours were provided during these short term closures, causing minimal traffic delays.
- *Minimal throw-away construction.* The demolition and rebuilding of roads and accompanying infrastructure, built previously adjacent to the bridge substructure, was minimized by advancing the specific parts of foundations and piers into construction contracts that preceded the bridge construction. Typically, caissons and associated piers that were close to the new bridge structures built previously, or in the vicinity of the roadway under traffic, were designed first and constructed under previous contracts. This generated additional cost savings and eliminated further traffic disruptions on finally completed roadways.
- *Short steel fabrication/delivery lead time.* Once the Owner decided to construct steel bridges, the steel plate rolling mills were contacted by the Owner to schedule production time that would correlate with the overall construction schedule at the Airport site. As a result, the lead time required to purchase, fabricate and deliver the steel boxes on site was minimized, and the erection of the boxes proceeded as soon as the substructure was completed.
- *Flexibility in modelling complex geometries.* With the available design tools and steel fabrication technology, construction of steel bridges in both horizontal and vertical curves is becoming

more common. The unusual site specific details of the structures are fabricated with high precision in the shop environment, ensuring they fit properly into existing geometry.

- *Short on-site erection time.* These single box girder bridges did not have exterior bracing, which is typically site installed, and the field splices were limited at the design stage to two per span. This allowed the erection time for the bridges to be, on average, two days per span. This includes the preparation, set up of equipment and actual erection.

In conclusion the use of single steel box girder bridges for the TPIA project was a success from both a cost and schedule perspective. Improved erection time and minimal traffic impacts are the benefits of using this type of structure. These benefits offset the possible adverse effects of steel price volatility.