FORT YORK PEDESTRIAN BRIDGES IN TORONTO. THE TWO FIRST DUPLEX STAINLESS STEEL BRIDGES ON THE ENTIRE STRUCTURE IN NORTH AMERICA

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BIOGRAPHY

Juan Sobrino, Ph.D., P.E., PEng, ing, ICCP, is the founder and President of PEDELTA Inc. with office in Coral Gables, FL, Toronto, Spain, Colombia and Peru. Juan earned a MSc (1990) and PhD (1994) in civil engineering from the Technical University of Catalonia (UPC). Juan is registered PE in four States and three Provinces in Canada. With more than twenty years of experience, he was the Engineer of Record for more than 400 bridges of all sizes and types. Juan is based in Toronto and has lead the operations of Pedelta in Canada since 2012.

Juan has extensive experience working in Design-Build and PPP bridge projects in North America, and Europe. He has performed the conceptual and detailed design of a wide variety of medium to long-span bridges in both steel and concrete. His experience includes the structural analysis and design of bridges for seismic design, dynamic rolling-stock analysis, soil and track-structure interactions and complex time-dependent analysis.

A number of Juan's designs have received prestigious awards for their elegance and innovative values. Juan is a frequent invited speaker on the use of advanced materials in bridges, bridge aesthetics and the design of high-speed rail bridges Juan was part-time professor for 17 years at the UPC in Barcelona (Spain) before he moved to North-America. Between 2011 to 2014 was Adjunct professor at Carnegie-Mellon University in Pittsburgh, PA.

SUMMARY

In April 2015, the city of Toronto selected a proposal for the Fort York Pedestrian and Cycle Bridge project in a design-build competition. The project provides a key link between Stanley Park to the north and the historic area of Fort York – the birth place of Toronto- crossing two rail corridors. Construction started in August 2016 and completion is expected by July 2018.

The project includes two pedestrian bridges. The awarded design proposal includes an unprecedented technical innovation in North America: the use of Duplex Stainless Steel on the entire structure. This pioneering use of a forefront technology provides premium aesthetics within a unique setting in addition to a safe and durable asset for the community. The structure has an extended life cycle, is more corrosion-resistant and requires less maintenance, reducing its overall cost.

Each bridge is supported by a single arch rib inclining at 18 º to provide a slender, transparent, and elegant impression. The two arches tilt in opposite direction, and the overall layout resembles a Yin & Yang shape to emphasize both contrast and continuity, expressing a modern, understated and elegant aesthetic.

This paper discusses the concept, detailed design, structural behaviour and bridge erection.

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Poject Overview

The new crossing will physically link a series of open spaces that extend from deep within the Niagara Neighborhood right down to the Waterfront in Toronto in the Fort York Area- national historic site and birthplace of Toronto-. Two new bridges over the railway corridors west of Fort York and pathways provide enhanced connectivity through these open spaces, offering cyclists and pedestrians a pleasant alternative to busy City streets. The City of Toronto, through Build Toronto, the City's real estate and development corporation choose a Design-Build procurement model to facilitate and optimal and cost-effective construction of this project. The key design challenge is how to achieve an appropriate landmark quality in this special heritage setting, within a very tight budget.

The awarded design proposal includes an unprecedented technical innovation in North America: the use of Duplex Stainless Steel on the entire structure. The bridges incorporate high quality, durable, natural finish materials throughout, highlighted by state-of the-art Stainless Steel components, complemented by contrasting traditional materials including wood, weathering steel, and stone.

The bridges present substantial curving forms within the landscape that are visually strong in a minimal, understated and elegant way, to touch the historic setting as lightly as possible. The expression is clearly contemporary but incorporates touches of traditional materiality that help complement the railway and Fort York setting. The design has been focused on both structural efficiency and pleasing proportioning of the geometry. Both bridges span the rail corridors almost perpendicularly to minimize the crossing distance, which leads to a 170 ft 6 in (52m) span for the North Bridge and 146 ft (44.5m) span for the South Bridge. Also, both bridges use trapezoidal cross sections for girders and triangular cross sections for arch ribs. The span-to-rise ratio is around 6 and the span-to-arch-depth ratio is around 100. To accommodate the 5m elevation difference between the ends of the South Bridge, a curved landing is proposed to gracefully connect the bridge to adjacent paths (Figure 1).

Figure 1. General View

Project Challenges

One of the key challenges was to design and build the bridge over the existing railway corridors own by Metrolinx, placing the substructure out of the right of way of the rail corridor and keeping a vertical clearance of 24.4 ft (7.44 m) above the top of rail. The bridges should have an unobstructed width of 16 ft 5 in (5 m) to accommodate both pedestrians and cyclist and are provided with universal access. The bridges cross over two active rail corridors so consideration must be given to protection, safety, and security of both the railway operations and the pedestrians and cyclists using the bridge.

The south approach lands on the Garrison Common-Fort York Area. Garrison Common is the treed open space west of the walled Fort, historically significant as one of the important battlefields in the War of 1812. It also serves as an important venue for Fort York programming and events. In order to minimize heritage impacts on the cultural heritage landscape of Fort York, the bridge and approach ramp within Garrison Common at Fort York is to have a minimal footprint. The landing should be kept tight to the rail corridor to keep the central portion of the Common open and functional, and the bridge must land 'lightly' on the Garrison Common in order to maintain the horizontal plane of the existing landscape. Grading solutions where up to 30% of the ultimate change in grade from the bridge deck to existing grade at Fort York is made up through solid fill, and a minimum of 70% through structure are acceptable.

The bridges are designed to add a distinctive visual element with a clear identity to the city of Toronto without dominating the skyline of the neighborhood.

The bridges had to be designed for a 75-year service life in accordance with the Canadian Bridge Design Code [1]. Durability was an especially important issue to consider for this project. One of the key points considered at the preliminary design phase when evaluating between the use of the stainless-steel option from an investment perspective, was to look at the lifecycle costs which includes all anticipated maintenance costs. The bridges will be permanently exposed to a potentially corrosive environment and de-icing salts in winter. The maintenance requirements for Stainless Steel structures is limited to regular pressure washing with water to clean the structure from de-icing salt accumulation as the duplex stainless-steel grades proposed for this project ensures a high corrosion resistance. In addition, Stainless Steel is particularly beneficial for structures with significant maintenance constraints such as bridges over railway or water as it will eliminate the need of major associated costs (worker's protection, flagging etc.) and indirect cost caused to the users during repair proceedings. Stainless steel combines many of the properties that were requested by the City of Toronto committed with a sustainable development

Duplex Stainless Steel

Stainless Steel is the name given to a family of corrosion and heat resisting steels with a minimum content of 11% Chromium and other controlled alloying element additions, each affecting the mechanical and chemical attributes to resist different corrosive environments. Stainless Steel is recognized as a sustainable material with a lower environmental impact than Carbon Steel (reduced CO_2 emissions due to fabrication, lightweight construction and low maintenance and deconstruction cost over the bridge lifespan) and one of the highest recycling rates of any material.

Stainless steels have been used in a variety of structural engineering applications ever since they were invented one hundred years ago and are ideally suited for a variety of uses. In addition to excellent durability, they can exhibit high mechanical properties. Stainless steels are primarily used in aggressive environments: near marine environments, where exposed to de-icing salts, or in very heavily polluted locations.

There are more than 100 types or grades of Stainless Steel which are typically classified in five basic groups: austenitic, ferritic, duplex, martensitic, and precipitation hardening. The duplex stainless steels are the most appropriate for primary load-carrying members in bridges.

Due to the high level of alloying elements and processing in stainless steel, there is an initial cost premium for stainless when compared to traditional carbon steel used in bridges. However, unlike galvanized or painted steel, the naturally-occurring corrosion resistant surface layer means there is no requirement for applying protective surface layers and no remedial work or corrosion risk at cut edges. Over the lifespan of a structure, eliminating the need for coating maintenance or component replacement due to corrosion can lead to significant long-term maintenance cost savings

Worldwide, the number of bridges being fabricated from duplex stainless steel as a primary structural component is steadily increasing, especially for pedestrian bridges. There are also a significant number of bridges employing stainless steel in secondary elements such as railings, bearings, or concrete reinforcing. In general terms, the strength, ductility, toughness and corrosion resistance of duplex stainless steel, such as the grade 2205 proposed for the Fort York Bridges, are higher than a regular carbon steel. The only construction challenges with the use of Duplex Stainless Steel are related with fabrication (not difficult but different).

Structural Design with Stainless Steel

The design of the two bridges is based on a detailed 3-D model structural static and dynamic analyses and is meeting all design safety and performance criteria of the Canadian Bridge Code CAN/CSA-S6. The stainless-steel structure has been designed in accordance with the design guidelines for Structural Stainless Steel (DG27) published by the American Institute of Steel Construction [2]. In general terms, DG27 is more conservative for the calculation of the resistance than the CAN/CSA-S6 Code and includes similar provisions to those used in the Eurocode for Stainless Steel Structures [3].

Pedestrian bridges are lightweight structures and might vibrate under live loads. To ensure that the proposed concepts are efficient, the preliminary design included the analysis of various structural configurations and materials. To ensure an adequate dynamic behavior, the bridge decks are proposed to be made of concrete in order to add the mass needed to meet CAN/CSA-S6 Code requirements. This is the main reason why it was decided to not use dampers or GFRP decks, in addition to their increased need for maintenance.

Detailed Design

The Design-Build Team proposed a unique Fort York arch design: a tied stainless-steel network arch with a distinctive crossing diagonal hanger pattern and a triangular cross section profile, with a single arch rib inclined at 18 degrees to provide a slender, transparent and elegant structure. The arches tilt in opposing directions for each bridge, to create a more dynamic visual experience for users - structures that are configured differently but still retain a continuity of expression (Figure 2).

The structural system selected for both bridges is similar, with a slightly different geometry.

North Bridge

The bridge has a single span with total length of 170 ft 6-in (52 m) between the axes of the abutments (Figure 3). The arch has a parabolic elevation with a maximum rise over the deck elevation of 29.5-ft (9 m) resulting in a dynamic and relatively flat rise-to-span ratio of 1:5.8 selected for aesthetics reasons. The hollow rib has a triangular cross-section 3-ft (900 mm) wide 1 ft 6-in (450 mm) deep with a central web made from steel plates with thicknesses ranging between 5/8-in and 1.6-in (15 and 40 mm). A triangular cross-section has been selected to benefit of the effects that sunlight will create, reinforcing its visual slenderness, as well as to facilitate fabrication utilizing standard hot-rolled steel plates.

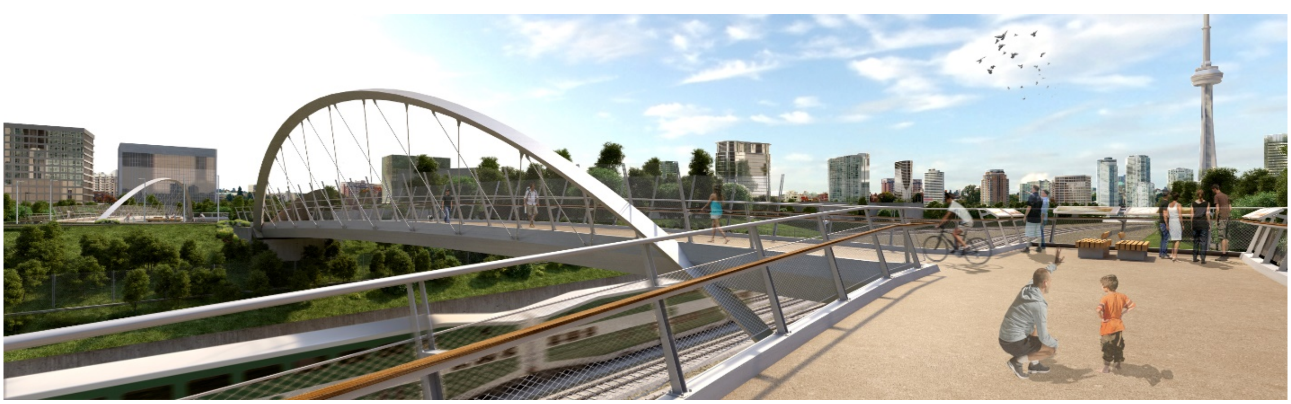

Figure 2. View on south approach looking east.

The arch is connected to the tie-girder at both ends and by two families of inclined hangers that cross each other once (Figure 4). The hangers are inclined 60 degrees to the horizontal and consist of 1.4-in (36 mm) diameter stainless steel rods that provide a clean a smooth appearance compared to traditional cables. This arch system is a very efficient structure; the arch works like a truss with minimum bending moments and shear forces, even for asymmetrical live loads unlike arches with vertical hangers. The triangulation of hangers provides restraint to the horizontal component of load due to the inclination and against buckling. Therefore, both the arch and tied-girder can have cross-sections with very slender dimensions that make the bridge more transparent and lighter. Hangers only take axial forces and work in tension. At both ends of the rods, an eye fork fitting provides length adjustment. The forks are connected to both the arch rib and the deck with steel plate gussets to create an elegant and simple pinned connection.

The steel deck system is connected with a 7-in (180 mm) depth concrete slab on top. The slab acts in composite action with the box girder and ribs to take advantage of the two materials. The concrete deck, unlike other lighter deck systems, provides the minimum mass and a higher damping ratio required to prevent excessive vibrations that would be, otherwise, uncomfortable for users.

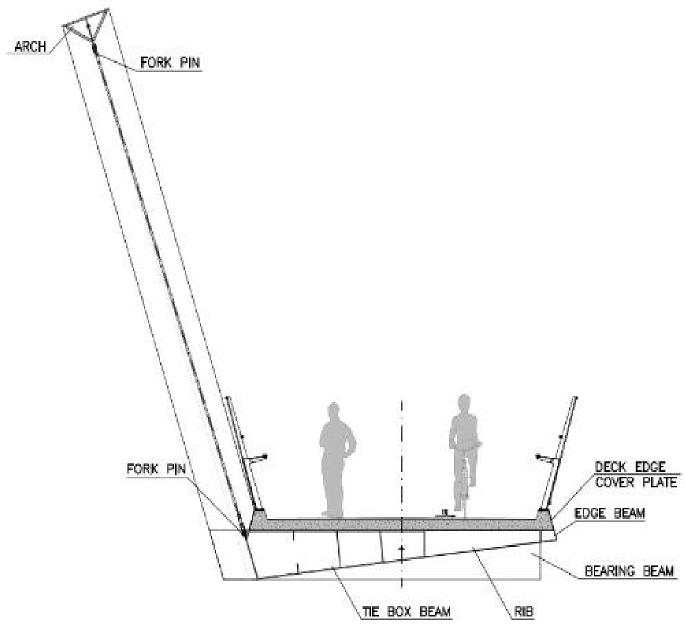

Figure 4. Typical Cross-Section

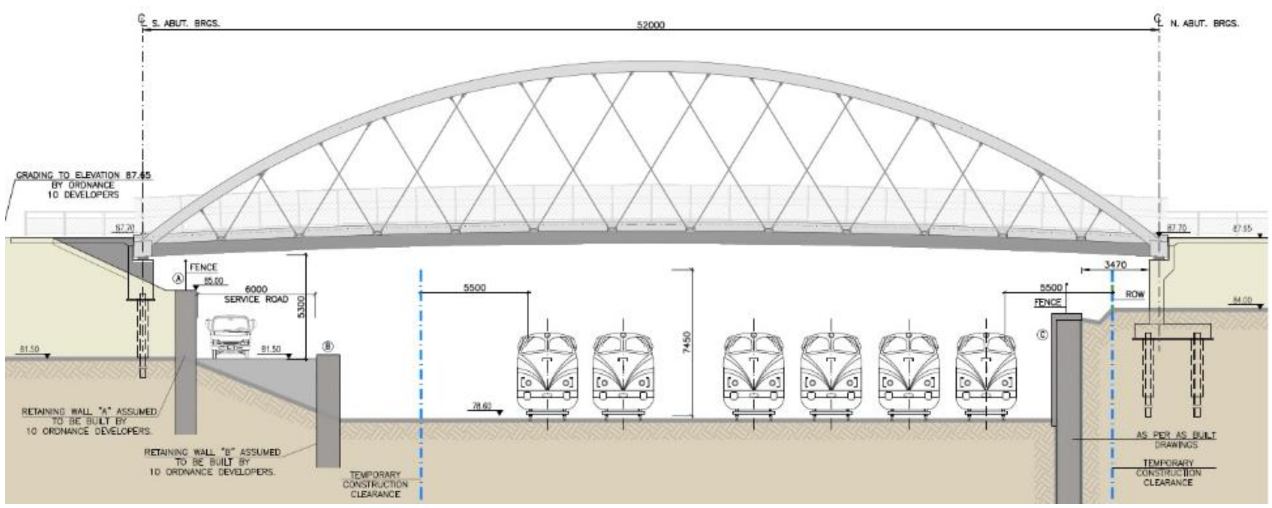

Figure 3. North Bridge Elevation.

South Bridge

Unlike the North Bridge, the south crossing links the Ordnance Triangle to Fort York with a 16 ft 5-in (5 m) elevation difference that imposes a different bridge design concept. After assessment of various arch alternatives, the solution that best fits the site constraints is a one-span arch connected to a V-shape pier on the south end. This unusual structural system will be very efficient as it transforms the thrust of the arch into a set of axial forces in the V-pier that also provides a greater openness underneath the crossing (Figure 6).

The 160 ft 9-in (49 m) long bridge will cross the Oakville Subdivision rail corridor with a straight alignment perpendicular to the tracks to minimize the length of the structure over the rail. The selection of the span length is based on the rail crossing size, aesthetics, creature comfort vibration criteria and economics. The span length between the axis of the abutment and the pier axis is 146 ft (44.5 m). The bridge platform extends to the south to blend with a curving approach structure oriented to the west with a projecting lookout to the East.

Similar to the North Bridge, the arch is inclined 18 degrees to the vertical, but here tilts towards the west to open up views towards the downtown skyline. The arch and tied-box girder features geometry similar to the one designed for the North Bridge with some adjustments of the arch width and various plate thicknesses that are adapted to the actual structural demand.

The South Bridge landing includes a 190 ft (58 m) long structural ramp on the west side terminating in a cantilevered lookout on the east side. The ramp is a continuous girder with typical spans of 39 ft (12 m) to minimize the structure depth and open up views underneath. It consists of a cast-in-place concrete slab with a trapezoidal cross-section. The maximum depth is 1 ft 6-in (500 mm), reducing to 1ft 1 in (344 mm) at the edges. The structure is continuous with the bridge and integral with the pier to minimize future maintenance. The piers have a trapezoidal cross section and are made of concrete. They have been shaped with inclinations to reflect the angle of the arch. The two side faces of each pier (and each side of the low fin wall that emerges out of the south earth berm) are clad in permanent weathering steel that provides a bold and natural material contrast with the stainless steel that helps visually ground the bridge in its heritage setting. The end of the ramp is supported on an abutment that uses the same concept utilized for the other abutments.

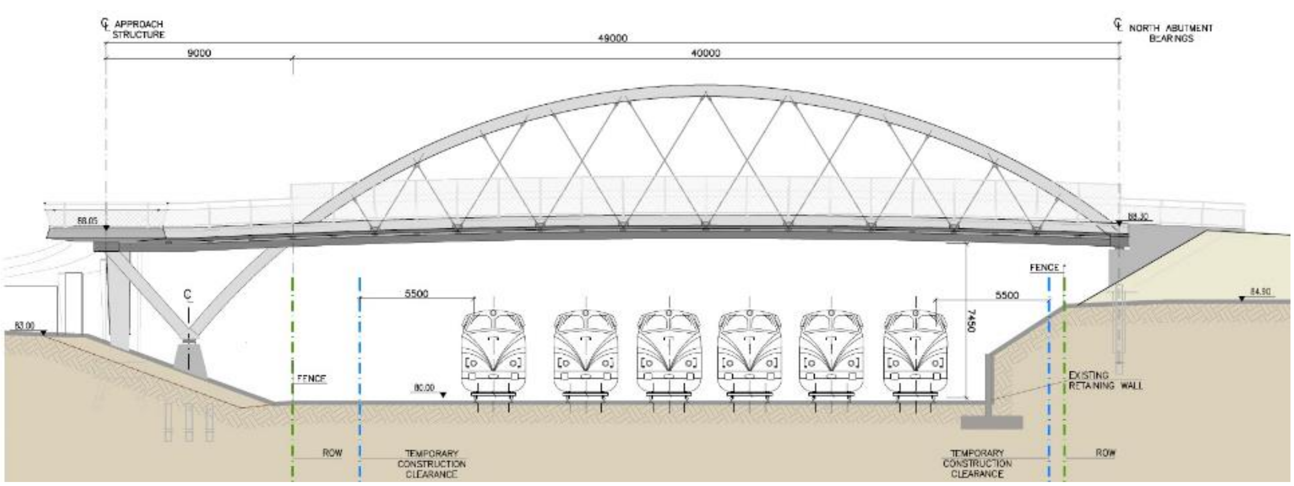

Figure 6. South Bridge Elevation.

Construction

Construction started in August 2016 and completion is expected by July 2018.

Substructure: Due to the presence of softened clayey soils, shallow spread footing foundations are not suitable for support of the pedestrian bridge abutments, and deep foundations have been adopted. Shallow foundations have been assessed for the more lightly loaded piers in the central and western portion of the sloped pathway on the Fort York property; however, deep foundations have been selected for support of this portion of the structure as well to enhance the differential settlement performance. The deep foundation solution consists of steel H-piles, fitted with bearing points and driven into the shale. The abutment and pier pile caps have been maintained as high as possible, to minimize excavation and groundwater control requirements

The project includes an innovative, flexible and attractive precast retaining wall with a reinforced soil system to retain the south and east faces of the North Landing and abutments. Face slopes are angled back slightly to provide a naturalized terraced stone effect that will blend well into the new South Stanley landscape and contrast effectively with the cast-in-place concrete bridge abutment (Figure 7).

Figure 7. North Abutment of the North Bridge.

Steel Fabrication: Fabrication and erection is carried out in accordance with the Design Guide for Structural Stainless Steel (DG-27) of the American Institute of Steel Construction. Welding is performed in accordance to the AWS D1.6/D1.6M. Stainless Steel is not a difficult material to work with. However, in some respects it is different from carbon steel and should be treated accordingly. It is crucial to preserve the good surface appearance of the stainless-steel surfaces throughout fabrication with simple precautions and good engineering practice

Great care is required in storing and handling Stainless Steel than carbon steel to avoid damaging the surface finish and to avoid contamination by carbon steel and iron. Stainless Steel can be cut by usual methods, but power requirements are greater than those used for carbon steel due to work hardening. Grade 2205 has excellent machining properties compared to other stainless steels.

The proposed duplex stainless-steel grade has excellent weldability and most of the typical welding methods such as SMAW, GTAW, GMAW, SAW among others can be used. The material should be welded without preheating and allowed to cool between welding passes to below 150ºC. Filler materials shall be used. Post-welding annealing after welding with filler is not necessary. Inspection of welds is carried out by AWS certified weld inspectors, duly experienced in welding Stainless Steel. Examination methods for welds are like those used for carbon steel. Ultrasonic methods have been tested to prevent difficulties of interpretation. In order to restore the stainless-steel surface and corrosion resistance after welding and fabrication, it is necessary to conduct a post-fabrication treatment such as pickling, brushing and blasting to remove all scale and contamination (Figures 8 and 9).

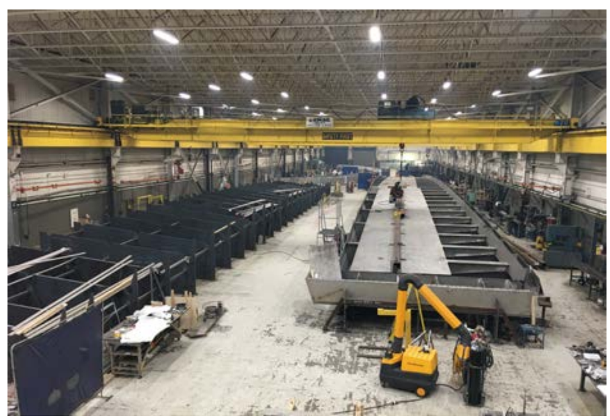

Figure 8. Steel Fabrication of box girder.

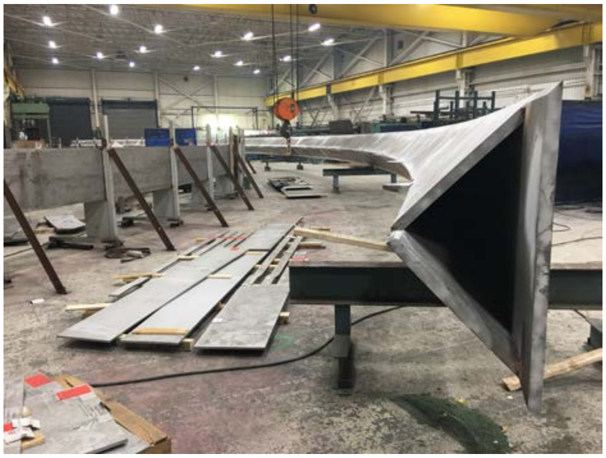

Figure 9. Steel fabrication of the arches..

Erection

The construction of the bridges will have its own challenges. The bridges have been conceived to minimize interference with the rail and streamline the construction time. Most of the bridge components are prefabricated at the shop and assembled at the site to accelerate construction and ensure quality. The steel parts are prefabricated in sections to facilitate transport to the site (4 sections for both the arch and the tied girder). Both the tied girder and arch are fabricated to the required camber to compensate for deflections due to all dead loads and match the design profile elevation (Figure 10).

All Stainless Steel visible surfaces will be bead blasted after pickling to get a consistent uniform dull finish with a natural silver colour and remove all scale and surface contamination arose from fabrication (Figure 11).

A key element of this strategy is to minimize the number of iteration of construction mobilization. Upon completion of access to the assembly areas, the bridges will be assembled and erected on the accesses to minimize noise and disturbances to neighboring residential areas in the north and to the Fort York. Upon delivery of the sections to the site, the arch and tied-girder sections will be erected in pre-set positions on temporary supports at close intervals without hangers. The main field splices are designed for field welding for aesthetic reasons. After completion of the arch and once it is connected to the tied girder, the arch will be released to take up its true shape. Then, the hangers will be installed, and hand tightened, and the intermediate supports of the tied girder removed to let the hangers take up their steel dead load tension. The bridge superstructure will be then put into the final position with cranes placed at both ends. The installation of the two bridges will be done at night during the weekends to avoid/minimize rail traffic disruption. This erection of this phase is expected in the spring of 2018.

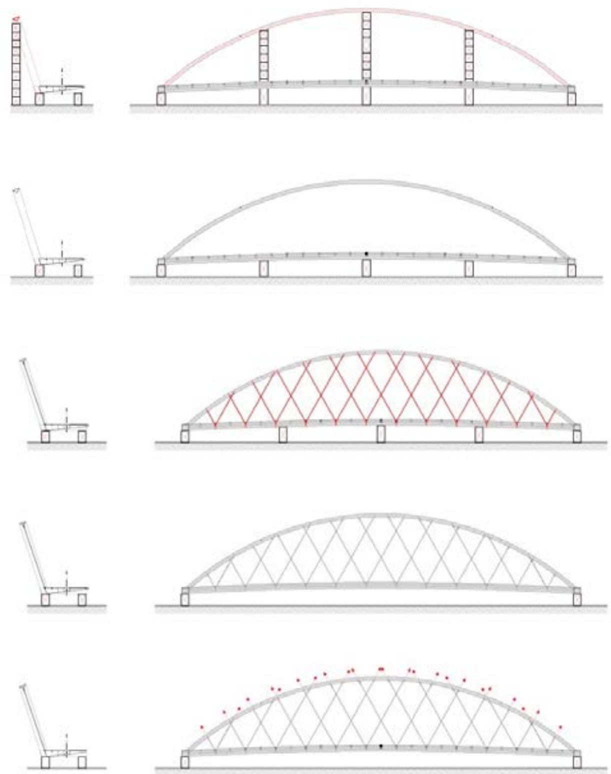

Figure 10. Bridge erection sequence.

Figure 11. Surface finish samples.

Upon placement of the steel structure, the installation of pre-cast partial depth concrete panels over the ribs will be done with small cranes for then pouring the top cast-in-place concrete deck slab. After this operation, the hangers will take up their final permanent load tension. The bridges will be completed with the finishes, including the illumination system. Bridge assembly and erection phases are conceptually shown in Figure 9. The reinforced concrete structural ramp on Fort York will be cast-in-place using traditional scaffolding after completion of the substructure.

Conclusions

The Fort York Pedestrian and Cycle Bridge Project includes a unique arch design: a tied stainless-steel network arch with a distinctive crossing diagonal hanger pattern and a triangular cross section profile, with a single arch rib inclined at 18 degrees to provide a slender, transparent and elegant structure, that is easy to build, with an extended lifecycle and little maintenance required. The proposed design in stainless steel was awarded within a design and build project context competing against other bridge alternatives using carbon steel.

The design has been driven by utilizing less material and energy, providing an extended life span and easy maintenance even if the initial cost is slightly higher. The initial higher construction cost of stainless steel is offset by the extended lifecycle of bridges that are more corrosion resistant, require low maintenance and last longer, which is reducing the overall cost of ownership. This represents a net advantage for the Owner, in addition to improving safety and long-term durability. One of the key points to consider when evaluating between the Carbon and stainless-steel option from an investment perspective, is to look at the lifecycle costs which includes all anticipated maintenance costs. The maintenance requirements for Stainless Steel structures is limited to regular pressure washing with water to clean the structure from de-icing salt accumulation as the duplex stainless-steel grades proposed for this project ensures a high corrosion resistance. In addition, Stainless Steel is particularly beneficial for structures with significant maintenance constraints such as bridges over railway or water as it will eliminate the need of major associated costs (workers protection, flagging etc.) and indirect cost caused to the users during repair proceedings.

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