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A LANDMARK CABLE-STAYED BRIDGE ALONG WITH ALTERNATIVE DESIGNS FOR A TWO-SPAN BRIDGE IN URBAN AREA

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ABSTRACT
This paper proposes three designs of a two-span bridge in Greater Toronto Area (GTA) as part of the capstone project course in the fourth year of an undergraduate program. The first bridge configuration is a cable-stayed bridge, while the second and the third bridge configuration are of conventional bridge types such as composite slab-over steel I-girder and box-girder superstructures, respectively. All three bridges were proposed to be built with semi-integral concept at their end supports over abutments. Unlike conventional bridges, an elegant cables-tower assembly along with a decking structure supports a cable-stayed bridge. Such hybrid system allows for shallow decks and multiple load paths/structural redundancy. Further, by utilizing high corrosion resistance materials, e.g. galvanized stay cables, the bridge can undergo minimal repairs throughout its expected life span which signifies its durability/sustainability. Yet, these types of bridges are relatively expensive and various challenges are associated with their design/construction due to the complexity of the structure geometry, unique behaviour and sophisticated construction staging. Therefore, a detailed structural analysis of the cable-stayed bridge was carried out through a finite element modelling (FEM) process that represents the sequence of construction including the cables pre-tensioning phase. Meantime, the other two alternative bridge configurations were analysed per the simplified method of analysis specified in the 2014 version of the Canadian Highway Bridge Design Code. The conducted cost analysis showed the slab-over-steel I-girder bridge system to provide the least construction cost, followed by the slab-over-steel box-girder bridges. However, the increase in cost of the cable-stayed bridge, by about 23%, can be justified given its superior aesthetics which fits the selection criterion of the desired landmark structure.

Keywords: Cable-Stayed Bridge, I-Girder Bridge, Box Girder Bridge, Parametric study, Landmark, Sustainability, Aesthetics, FEM, Cost Analysis.

1. INTRODUCTION

Nowadays, major cities are facing increased traffic due to numerous reasons of which are the rise in human population, being the center of job attraction and business, and the declining capacities of existing infrastructures. The subject project responds to the need for a bridge to cross a water stream in the Greater Toronto Area (GTA). The bridge is proposed to reduce traffic and ease the congestion on the currently used roads, as well as to provide a landmark structure for the area. The proposed bridge has two equal spans of 20 m with pedestrian access through a 1.5 m wide sidewalk on each side of the bridge cross-section. Herein, a cable-stayed bridge is considered one of the most successful alternatives to be investigated for its unique combination of structural sophistication and architectural elegance. Examples for this type of bridges include the Millau Viaduct in France which is the world's tallest bridge (see Figure 1a) and Avenida Coronel Francisco H. dos Santos Bridge in Brazil as shown in Figure 1b. However, in order to quantify the cost premium that will be spent for such high aesthetics, a more common type of structures has been investigated as well in the form of a concrete slab-over steel I-girder bridge and a steel box girder bridge. In all cases, the safety and durability measures of both alternatives are intended to achieve those targeted by the applicable design standards (e.g. Canadian Highway Bridge Design Codes (CHBDC, 2014). The durability aspect, as considered a fundamental approach towards sustainability, has been tackled through materials with superior durability such as the non-corrosive Glass Fibre Reinforced Polymer, GFRP, reinforcement for the concrete components with intense exposure to environmental conditions. Further, high resistance steel types such as atmospheric, galvanized and stainless can be used for the steel components (e.g. girders and cables).

(a)

(b)

Figure 1: a) The world's tallest cable-stayed Bridge 'Millau Viaduct', France

(photo reference; http://twistedsifter.com/)

b) Avenida Coronel Francisco H. dos Santos Bridge, Brazil

(photo reference; https://structurae.net)

2.0 PRELIMINARY DESIGN PHASE

2.1 Loads

The main loads considered for the bridge design included: permanent loads (e.g. dead load, superimposed dead load) and transitory loads (e.g. live loads). The dead loads include the self-weight of the structural components (for example: girders, deck slab and haunch). While the superimposed dead loads included the pavement, sidewalks and barrier walls. For the live load, the standard truck shown in Figure 2, CL-625-ONT, was used along with the dynamic load allowance according to the CHBDC. In addition, the active earth pressure load was considered as it acts on the sidewalls. Loading cases were performed to maximize the effects of the transitory loads on the structure.

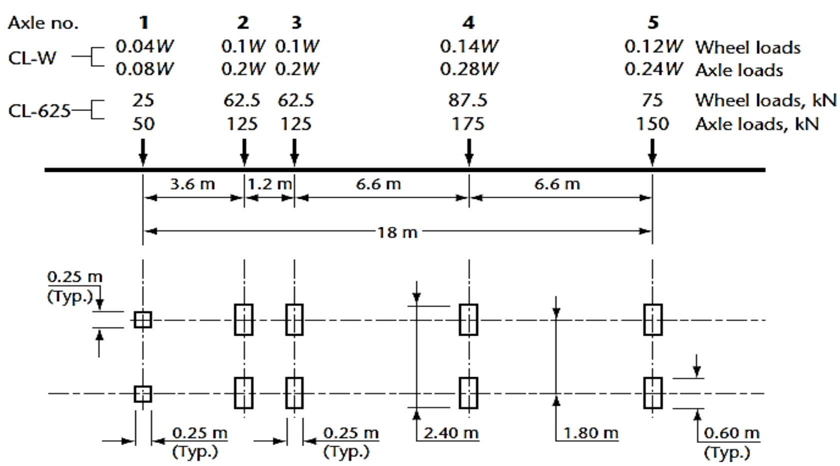


Figure 2: CL-625-ONT truck according to CHBDC

2.2 Cable-Stayed Bridge Alternative

2.2.1 Bridge Description

The bridge is proposed to overpass a water steam and a trail/sidewalk under the left span, and a street under the right span as depicted in Figure 3. The bridge deck accommodates two traffic lanes and two sidewalks, one in each direction, as depicted in Figure 4. A series of cables, along the longitudinal centre line of the bridge, connects the superstructure to the tower/centre pier. The substructure of the bridge consists of two abutments (at the edge supports) and a tower/pier (as an intermediate support) while footings supported by piles form the foundations. The piles are in both vertical and inclined orientations in order to provide support against normal, shear and moment forces acting on the footings.

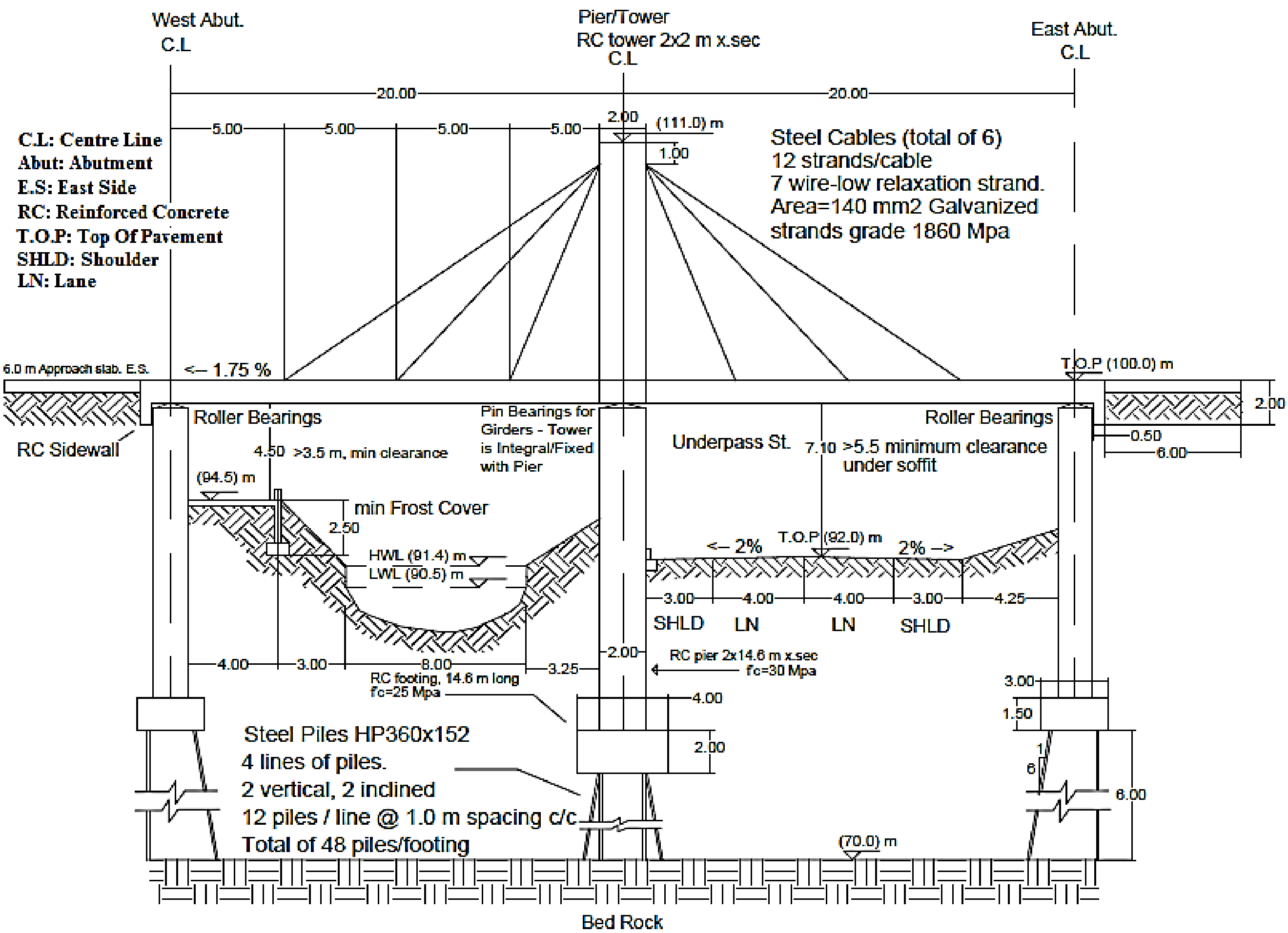


Figure 3: Elevation of the cable-stayed bridge alternative (Dimensions are in meters)

2.2.2 Proposed Construction Approach

The word Constructability is understood as the "optimal use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (Construction Industry, 2017). The construction of cable-stayed bridges is made possible with the use of balanced-cantilever construction as shown in Figure 5. It is the most common method used in their erection. It permits overhead construction while maintaining traffic below. Construction can proceed over deep valleys, navigable channels, and congested urban areas with little damage done to areas adjacent to the construction site.

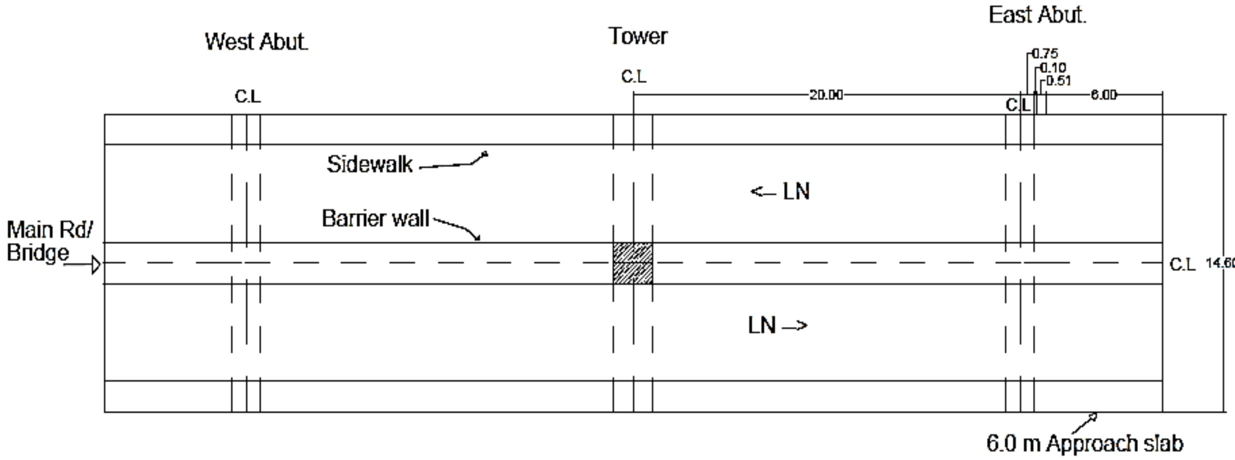


Figure 4: Plan view of the cable-stayed bridge alternative (Dimensions are in meters)

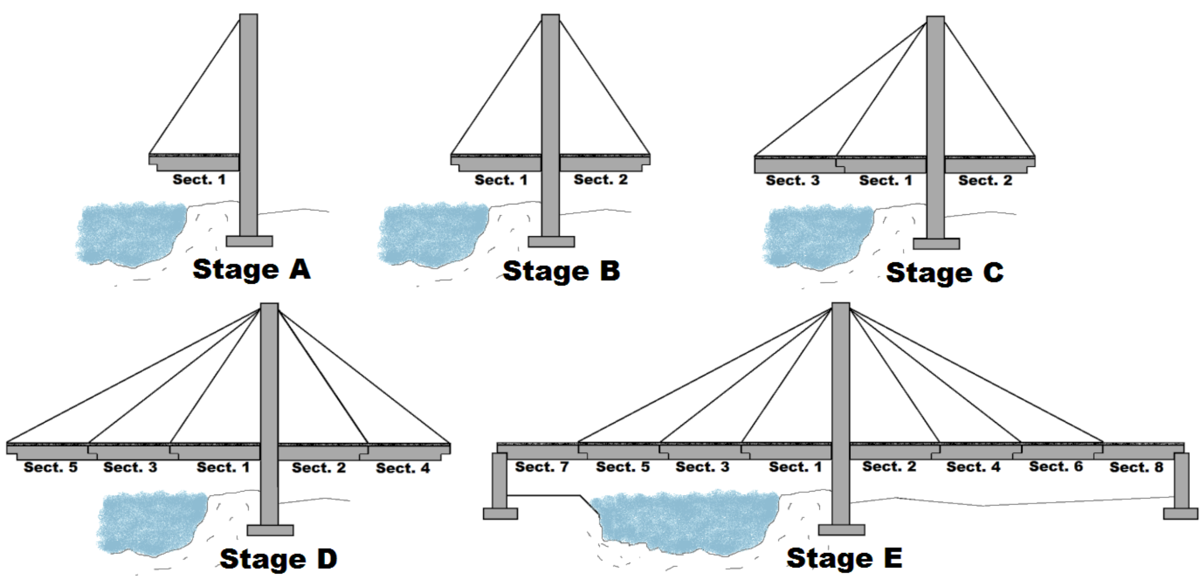
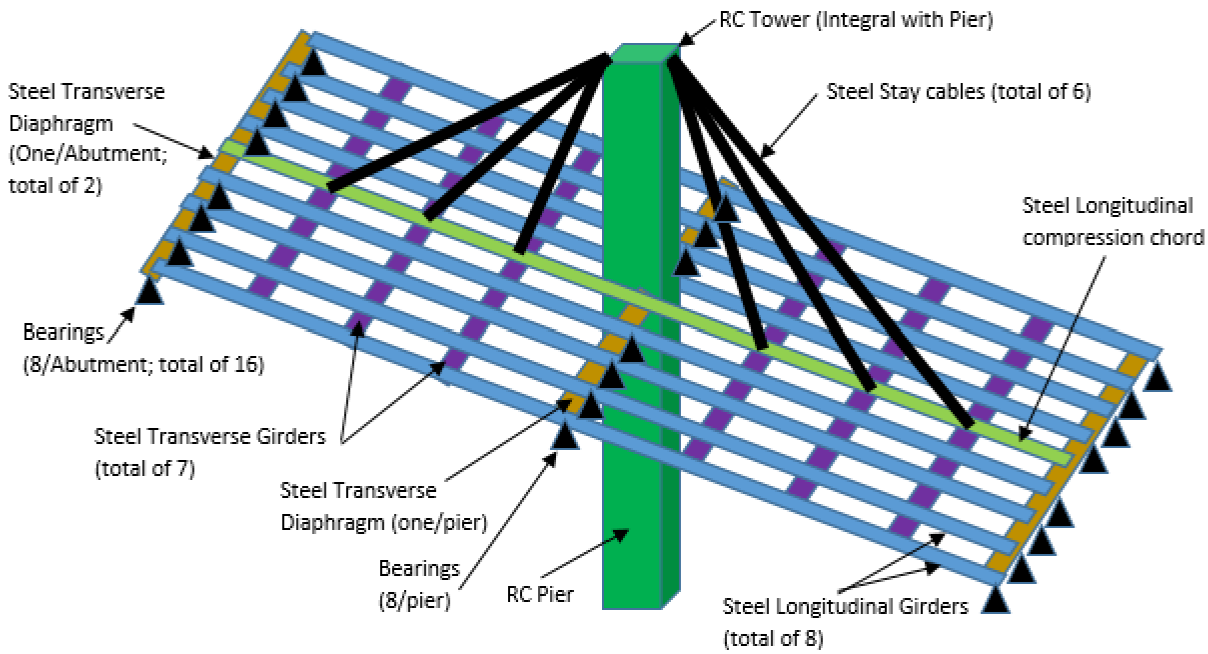


Figure 5: Proposed construction stages of the cable-stayed bridge alternative

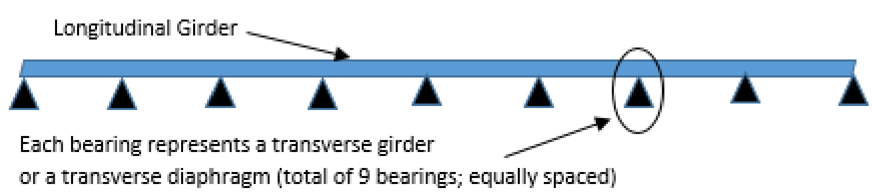
2.2.3 Analysis and Design Approach

This section explains the load transfer path of the proposed cable-stayed bridge. The bridge deck transfers the loads to the longitudinal I-girders where the deck slab acts compositely with the supporting girders using shear studs. It can be seen from Figure 6a, there are 8 longitudinal I-girders, that are carried by transverse double-cantilever I-girders running across the bridge at the locations of the cable-deck joints (Figure 6b). The torsion experienced by the bridge along its longitudinal axis due to the offset of vehicular traffic and/or wind loads, is eliminated from the transverse girders, by a set of forces acting on the longitudinal girders as shown in Figure 6(c). Further, to maintain full stability/resistance for such torsional effects, the longitudinal girders, and transverse diaphragms, are supported at the substructure (pier and abutments) directly by bearings. Finally, the cables carrying the transverse I-girders transfer their loads to the tower which is integral with the bridge pier as shown in Figure 6(a). An additional steel longitudinal girder is running longitudinally through the superstructure to form a compression chord of the cables system.

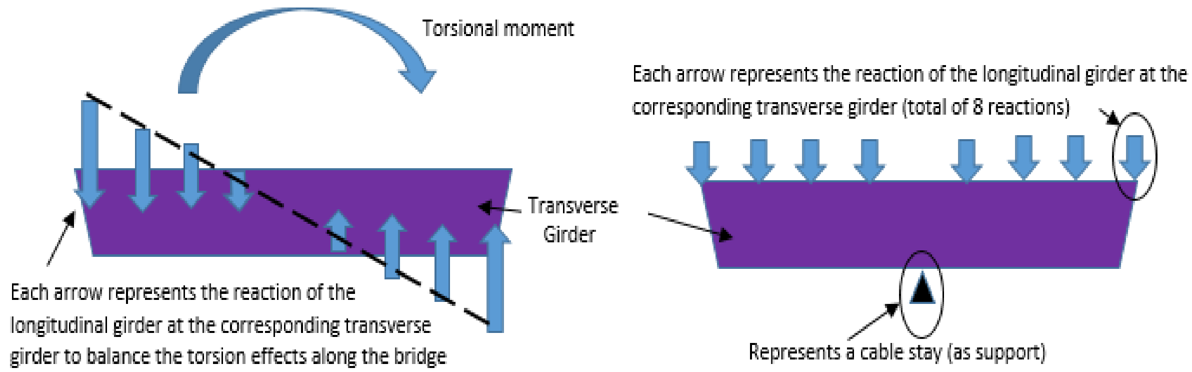
Due to the nonlinear structural behavior, especially considering the bridge construction staging, and in order to optimize the analysis process, the non-linear three-dimensional finite element modelling has been simplified into a series of a linear two-dimensional problems as depicted in Figure 6 using SAP2000 software (Computers and Structures Inc., 2014). Further, to obtain an optimum distribution of post-tensioning cable and to minimize the bridge deflection, the pre-tensioning force of the cables has been designed to lift the superstructure own weight by means of limiting the corresponding deflection to a zero with a tolerance of only ± 5 mm.



(a) Isometric view of the bridge skeleton (deck slab is removed for clarity)



(b) Structural system for longitudinal girders



(c) Structural system for double-cantilever transverse girders

Figure 6: Load transfer mechanism in cable-stayed bridge

2.2.4 Analysis Results and Design Check

Analysis results included the straining actions induced in the bridge components (e.g. bending moments, shear forces and axial loads) as well as the corresponding deformations (e.g. girder deflections). Series of checks were conducted according to the CHBDC for all the superstructure components (e.g. girders and cables), substructure components (e.g. tower, pier and abutments) and foundations (both pier and abutments' piles). This step proved the preliminary design to have a reasonable margin of safety that can accommodate additional straining actions that might be obtained during the detailed analysis/design phase.

2.3 I-girder Bridge Alternative

2.3.1 Bridge Description

The second alternative of the two-span bridge is the two-span composite concrete-deck slab over steel I-girders as shown in Figures 7 and 8. In 1997, Ontario Ministry of Transportation published a manual for standard short span steel bridges. The manual provides design tables for W-shape girder sizes required or slab-on-steel girders with specified spacing between girders, number of intermediate diaphragms and number of design lanes. This manual was considered as a guide to determine the W-shape steel girder size of the second bridge alternative on which the bridge cross-section is formed of 8 parallel girders as depicted in Figures 7 and 8. Transverse bracing was placed at the quarter points as well as at the supporting lines to stabilize the girders during construction and to assist in the structural integrity of the bridge superstructure while in service. The simplified method of analysis specified in CHBDC of 2014 was used to determine moments and shear forces at ultimate and fatigue limit states and live load deflection at serviceability limit state.

The main difference between the I-girder bridge and the cable-stayed bridge is the absence of the cables and the tower. Thus, all loads are transferred through the box girders to the substructure/foundations. In addition, eliminating the tower and the cables allows the deck to accommodate an emergency lane in between the two main traffic lanes.

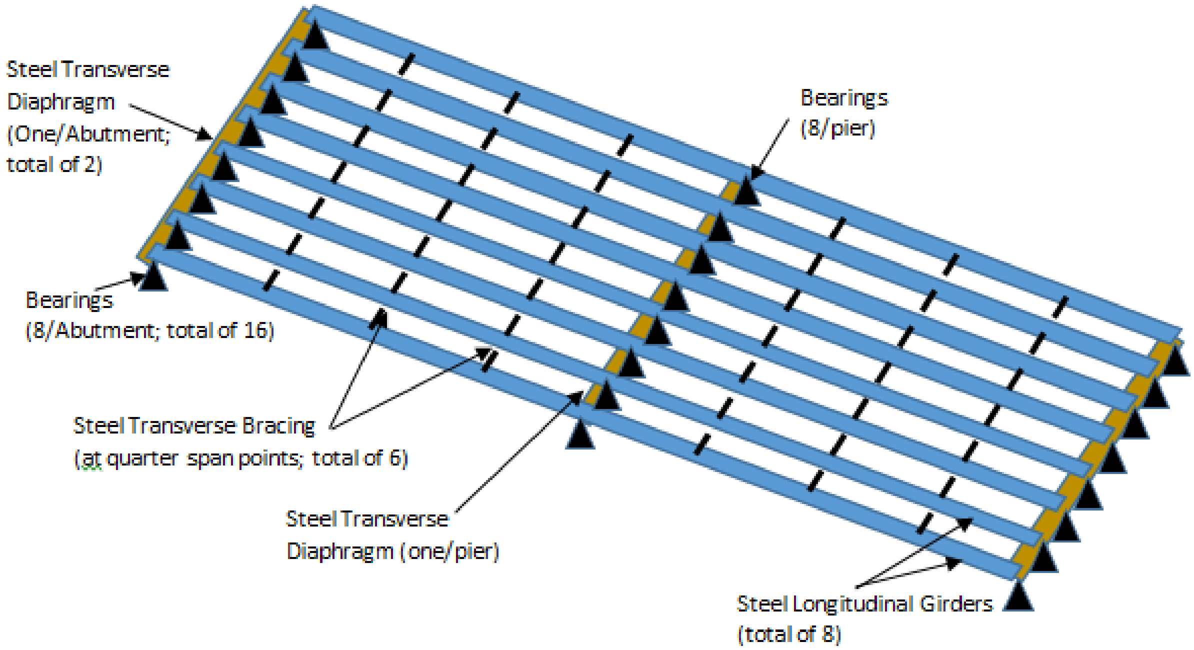


Figure 7: Isometric view of bridge skeleton (deck slab is removed for clarity)

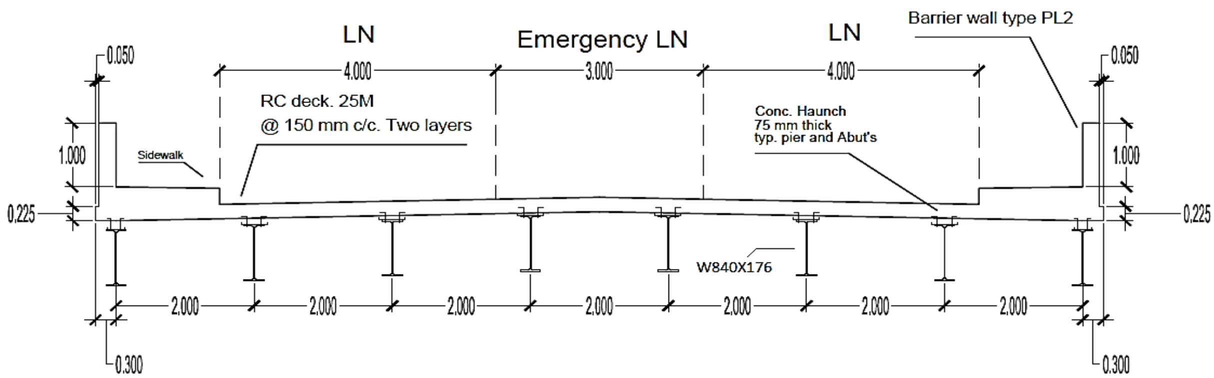


Figure 8: Cross-section of the slab-on-steel I-girder bridge alterative

Other advantages of this alternative are the significant simplicity of design and construction and higher torsional resistance. On the other hand, the relatively much lower aesthetics standards of this alternative compromises the essence of the project which is building a high profile/landmark bridge. The components of this bridge deck (riding slab, sidewalks, barrier walls and approach slabs), as shown in Figure 8, are identical to those of the cable-stayed bridge alternative. Also, the substructure for this option is assumed to be the same as that of the cable stayed option for preliminary design purposes.

2.3.2 Design Approach

Similar to the process done for the cable stayed bridge design, all the factored straining actions (e.g. factored bending moments, shear forces and axial forces) were obtained through the FEM/structural analysis. Critical design sections of the structure were checked as per the CHBDC and proved to possess greater capacity than the demands with a reasonable margin of safety.

2.4 Box girder Bridge Alternative

In this alternative, as illustrated in Figure 9, 4 box girders are proposed instead of the 8 I-girders of the I-girder bridge option. Moreover, the box girders possess a slightly better appearance than that of the I-girders along with a much better torsional resistance.

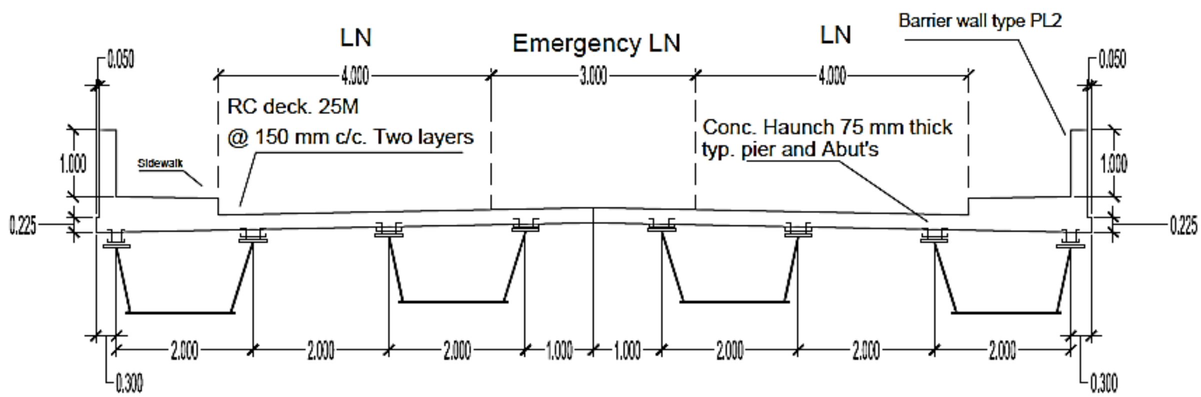


Figure 9: Cross section of the box girder bridge alternative (Dimensions are in meters)

3. OPTIMUM BRIDGE OPTION

The criterion for selecting the most suitable bridge option is based on comparing between the investigated alternatives from different aspects as discussed in the following paragraphs.

3.1 Design

The cable-stayed bridge is a unique option due to its complex structural behavior and unconventional construction. Such system requires profound understanding of the different components of the bridge from both design and construction as the designer needs to reflect the construction stages on the design itself. On the other hand, the simple analysis/design of I-girder and box girder bridges reduces the associated challenges and risks. However, it has to be noted that box girder bridges provide high torsional rigidity and resistance compared to the I-girder ones.

3.2 Construction

The construction of the cable-stayed bridge mandates various sophisticated trades and subcontractors, especially regarding the installation and pre-stressing of cables. In addition, many construction steps should be phased (cannot be overlapped) which requires longer schedule and precise construction staging bearing in mind the risks of delays. Conversely, the box girder and I-girder bridges are common structures which can be constructed quickly and with low risks.

3.3 Sustainability

Sustainability is a major aspect of the optimum option selection criterion. The environmental impact of each option is evaluated from the bridge construction to the end of its service life. The bridge structural system and the durability of the used materials have significant influence on the overall sustainability of the bridge. This sustainability is obtained by using less material, having an increased redundancy and low maintenance/repair. Unlike conventional bridges, a cable-stayed bridge is supported by cables and a deck system, thus allowing for shallower deck and hence less material usage. Further, this provides more redundancy than conventional bridges where in case of a failure in one of the girders (or cables), a cable-stayed bridge can still be supported by remaining cables and girders; allowing it to withstand extreme loading conditions.

Steel corrosion plays a major role in determining the bridge maintenance, repair and partial replacement during its service life as well as the end of the service life itself. Therefore, the durability of proposed bridge alternatives can be significantly improved through the usage of a combination of steel with high corrosion resistance and non-corrosive materials as follows:

- The steel sections used for girders can receive high corrosion protection measures such using atmospheric grade of steel (e.g. AT grade as per CHBDC) or galvanized steel;
- The bridge reinforced concrete components subject to high environment exposure/ accelerated corrosion such as sidewalks, barrier walls and top of deck, the non-corrosive glass fibre-reinforced polymers (GFRP) bars can be used instead of steel reinforcement; and
- The bridge cables, for the cable-stayed option, can be of either galvanized or stainless steel strands.

Additionally, the I-girders of both I-girder and cable-stayed bridge options provide continuous access without visual barriers to the entire components of the bridge girders which allows for frequent low cost inspection of the bridge. These frequent inspections will help an early detection of any damage in the steel girders or the concrete slab which will minimize the material, cost and time of any required maintenance and repair along with prolonging the lifespan of this bridge. In contrast, due to the closed nature of the steel box girder option (even with the provision of access hatches), it is more challenging and expensive to inspect and identify any possible damages, especially in the deck concrete slab segments above the top flanges of the girders.

3.4 Aesthetics

This project has an ultimate objective of providing a Landmark Bridge for the GTA, meaning that aesthetics is a major key to the decision-making stage. The cable-stayed option is a high-profile option where its graceful cables and shallow girders emphasize its architectural elegancy. On the other hand, the box girder and I-girder bridges are conventional options with no significant superiority of its architectural style.

3.5 Cost

The comparison between the initial costs of the superstructure of the investigated alternatives is summarized in Table 1 below. The rest of the bridge components were not included as they were considered of approximately the same magnitude. It can be observed that the cable-stayed option has higher cost for the initial construction. However, the significant reduction in future maintenance and repair costs, as discussed earlier, is estimated to impact the life cycle cost (LCC) of the bridge towards an overall less expensive alternative.

Table 1: Initial cost comparison between the three bridge alternatives

	Cable-Stayed Bridge	**Box Girder Bridge**	**I-Girder Bridge**
Cost of Steel Girders	$1,679,000	$1,518,000	$1,430,000
Cost of Tower	$70,840	-	-
Cost of Stay Cables	$17,628	-	-
Total Cost	$1,767,108	$1,518,000	$1,430,000

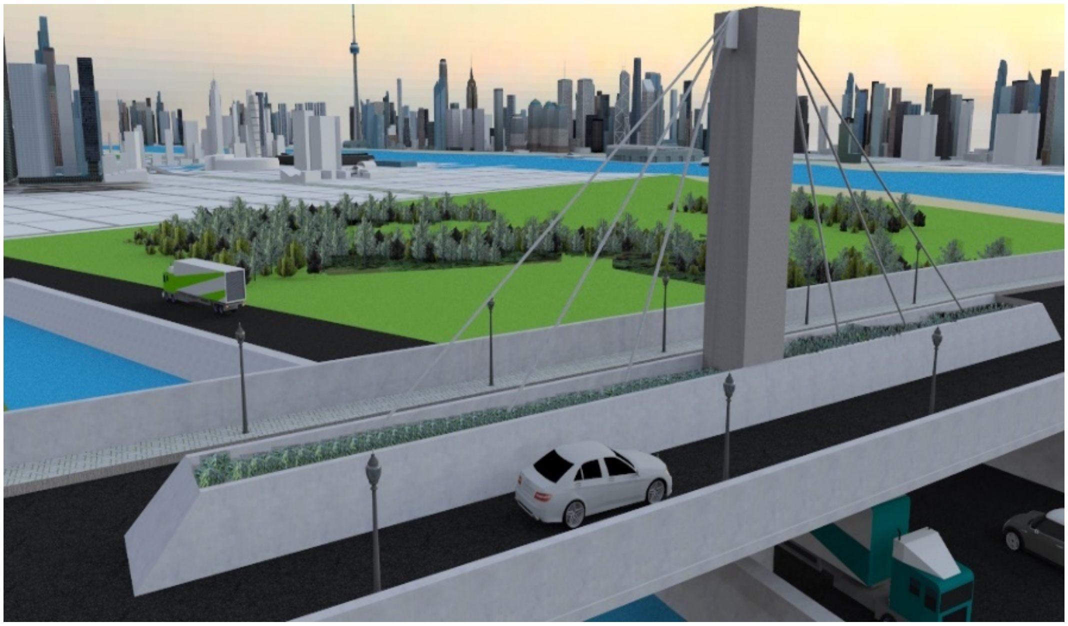


Figure 10: Rendered 3D view of the proposed cable-stayed bridge

4.0 RECOMMENDATIONS

Considering all the above-mentioned aspects of the selection criterion, and with high priority to the ultimate objective of providing a Landmark Bridge, the cable-stayed option is considered a perfect fit for the project. Therefore, this alternative became the sole focus of the final design phase of the project.

5.0 FINAL DESIGN PHASE

The secondary loads not considered in the preliminary design phase were being addressed herein (e.g. temperature effects). The refined FEM allowed investigating the straining actions induced in each individual component of the bridge. The various fatigue, serviceability and ultimate limit states (e.g. FLS1, SLS1, and ULS1 to ULS4) as per the CHBDC requirements were reflected on the bridge design. Moreover, the design of structural details such as the shear connectors/studs between concrete slab and girders and the connections/field splices of girders were completed.

6. CONCLUSIONS

Based on the performed preliminary design, and the foregoing final/refined analysis and design phase, of the subject project, the following recommendations and conclusions can be obtained:

- Cable-stayed bridges are characterized with complex structural behavior and unconventional construction. Extra care needs to be given during their design and construction.
- The sustainability/durability can be significantly improved through the usage of a combination of high corrosion resistance steel and non-corrosive materials. However, the cable-stayed option provides continuous access without visual barriers to the entire components of the bridge girders which allows for frequent low cost inspections that will minimize the future maintenance/repair and prolongs the lifespan of this bridge.
- The significant reduction in future maintenance /repair cost can impact the life cycle cost (LCC) of the bridge towards an overall less expensive alternative despite the higher cost of the initial construction.
- This project has an ultimate objective of providing a Landmark Bridge. Therefore, the cable-stayed option with its architectural elegancy and superior aesthetics is highly recommended/qualified as a best fit for the subject project.

6. REFERENCES

"Avenida Coronel Francisco H. Dos Santos Bridge (Curitiba, 2014)." Accessed February 3, 2017. Https://Structurae.Net/Structures/Avenida-Coronel-Francisco-H-Dos-Santos-Bridge.

CHBDC. 2014. Canadian Highway Bridge Design Code, CAN/CSA-S6-14. Canadian Standard Association, Toronto, Ontario, Canada.

Computers and Structures Inc. 2014. Integrated structural analysis and design software, SAP2000. Berkeley, CA, USA.

Construction Industry. 2017 "Constructability Concepts File". Accessed January 22, 2017. Https://www.construction-institute.org/scriptcontent/more/sp3_3_more.cfm.

MTO. 1997. Manual for Standard Short Span Steel Bridges. Ontario Ministry of Transportation, St. Catharines, Ontario, Canada.

"*The Tallest Bridge in the World [20 Pics]*." June 9, 2011. Accessed February 2, 2017. Http://Twistedsifter.Com/2011/06/Worlds-Tallest-Bridge-Millau-Viaduct-France/.