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A LANDMARK CONCRETE ARCH BRIDGE WITH AN INNOVATIVE APPROACH: POST-TENSIONED TIE GIRDERS

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Abstract: One of the oldest datable structure are arch bridges. Their unique geometry enables to transfer the loads along a curved path to supports; a simple yet a quite robust mechanism. This distinctive characteristic makes arch bridges one of the most popular bridges of all times. For the present project, the Greater Toronto Area (GTA) needs a bridge to carry pedestrian/bikers as well as vehicular traffic over a water stream that passes through a scenic valley/woods. The project investigates two superstructure alternatives; a Bow-string concrete arch and a side by side CPCI Box Girders. The first phase of the project (preliminary design) includes a simplified analysis, design and quantity/cost estimation of each alternative. A comparison is performed considering various aspects such as cost, durability, aesthetic and traffic impacts. Due to the highly aesthetic requirements of a landmark structure, the arch bridge is favoured. The second phase (detailed design) focuses on refinement of the applied loads and analysis to provide detailed design and drawings. In order to optimize the design and construction cost, a post-tensioning system is introduced to the arch tie girders. Such unique approach improves the bridge stiffness and induces both compressive stresses and upward deflection (camber) in the structure. This significantly reduces the tensioning/cracking and the final bridge deflection. In other words, it lessens the long-term repair/maintenance cost and improves the appearance of the bridge. The present paper details the design approach to optimize the cost along with improving the aesthetics, performance and sustainability of the subject bridge.

1 INTRODUCTION

1.1 Background

Many of the modern bridges around the world represent the pinnacle of bridge engineering of their generation. Such bridges function on three distinct levels - utilitarian, aesthetics and symbolic. Today, the utilitarian function of a bridge is quite obvious: a bridge is built for the safe passage of traffic and pedestrians from point A to point B without comprising the structural integrity. Aesthetically, a bridge should have a pleasing architectural feature and should be harmonious with its surrounding. Symbolically, a bridge represents uniqueness, rapprochement, or an understanding and in some cases can represent a place.

The rapid growth of the Canadian economy and the development of the population growth has led to the sudden increase in traffic volume particularly in the Greater Toronto Area (GTA). This rapid increase resulted in the diseconomy with problems such as the increase in commute times due to the traffic congestion and traffic accidents. Thus, there has a been a constant demand for increasing new traffic infrastructure, such as roads, highways and bridges for the past few decades to accommodate such growth.

The paper herein presents the design of two different types of bridges; a bow string arch bridge (Figures 1 and 2) and a side by side box girder bridge (Figure 3). The bridge is proposed to be built in the GTA over a water stream in order to minimize commute times and most importantly have the three distinct levels e.g. utilitarian, aesthetics and symbolic.

1.2 Project Description

The bridge alternatives of interest will both have the same substructure and consist of a two-way traffic system. Each alternative will be a 30 meters center-to-center single span and simply supported at the East and West abutments respectively. From a plan view, both bridges will, in a one-way direction, have a 4 meters vehicular lane, a 1.50 meters bike lane and 1.50 meters side walk lane (Figure 4 and 5). The bridges will also consist of a semi-integral abutment configuration. This means that the bridge deck will be continuous throughout with no expansion joints within the structure (Hussain and Bagnoriol, 1999). A joint will be provided between the outside face of the ballast wall and approach slab. Ripraps will be used in both alternatives to armor the abutments and piles against scour and ice erosion. Pile foundations will be used in both bridges to accommodate the site soil conditions.

Figure 1: 3D Rendering of Alterative I

As to the superstructure, the bow-string arch bridge as shown in Figure 6 is composed of a concrete arch girder located on each side of the roadway, a post-tensioned tie beam associated with each arch girder and a deck system supported by each tie beam. The deck system is mostly consisting of a concrete slab deck supported by five transverse floor beams. Five hangers connecting each arch girder to the tie girder are also present. The other alternative represents a 12 side by side box girders (Figure 7). Each box girder will rest on its own bearing. All girders are of B-1000 type and are pre-stressed (CPCI Box Girders).

1.3 Proposed Construction Approach

In order to shorten the construction period, an Accelerated Bridge Construction (ABC) can be implemented (Wisconsin Department of Transportation, 2009). This approach has three main techniques: GIS-IBS (Geosynthetic Reinforced Soil-Integrated Bridge System) and slide-in-bridge construction. GIS-IBS is 20-

60% more cost effective than conventional methods. This method also eliminates “bumps” at the end of the bridge, which is a common problem while building the abutments.

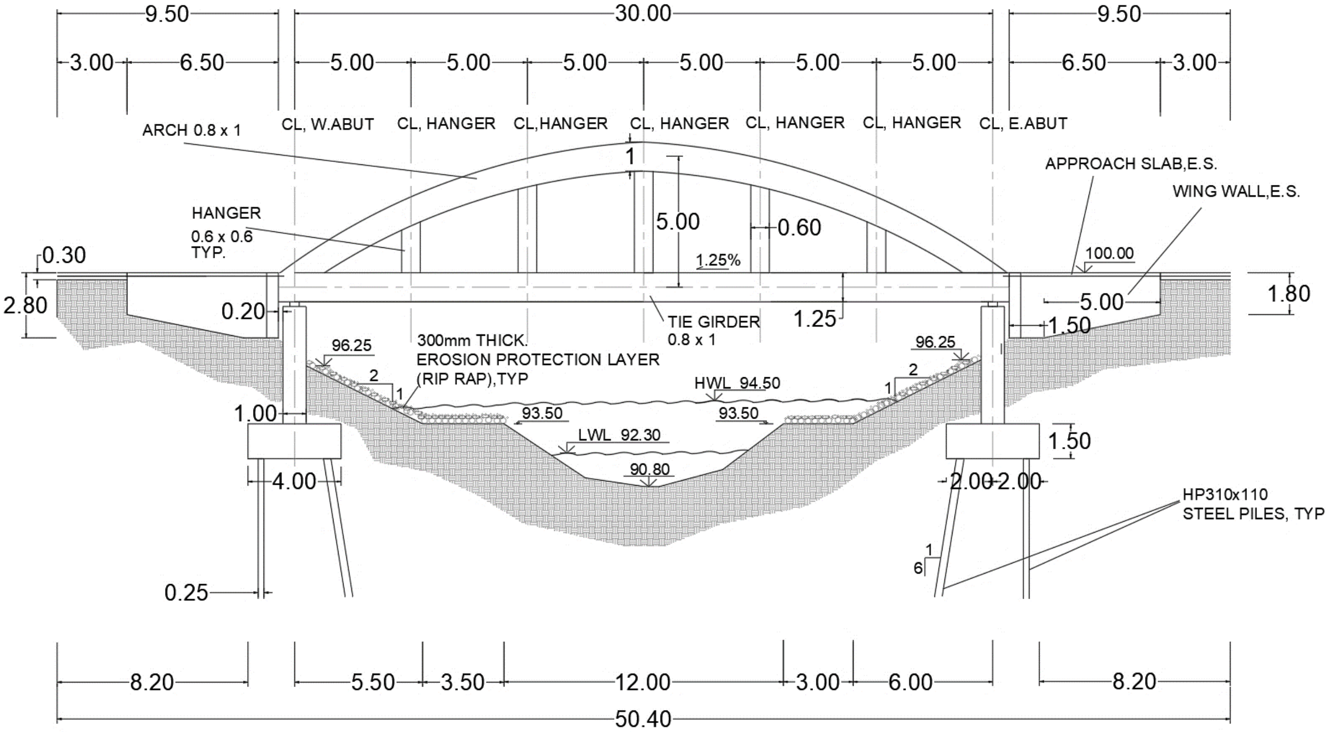

Figure 2: Alternative I Elevation (Meters Unit)

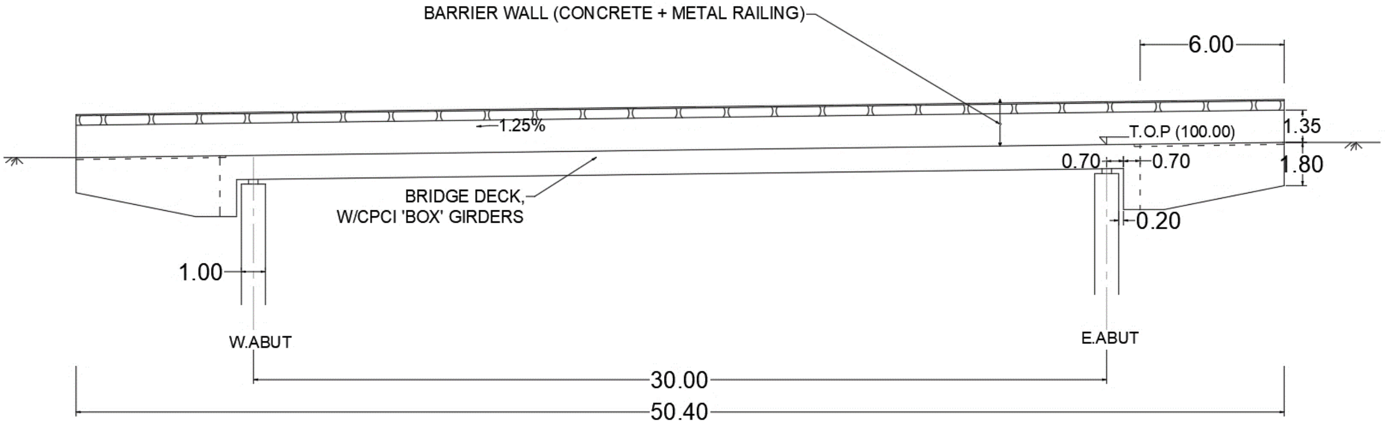

Figure 3: Alternative II Elevation (Meters Unit)

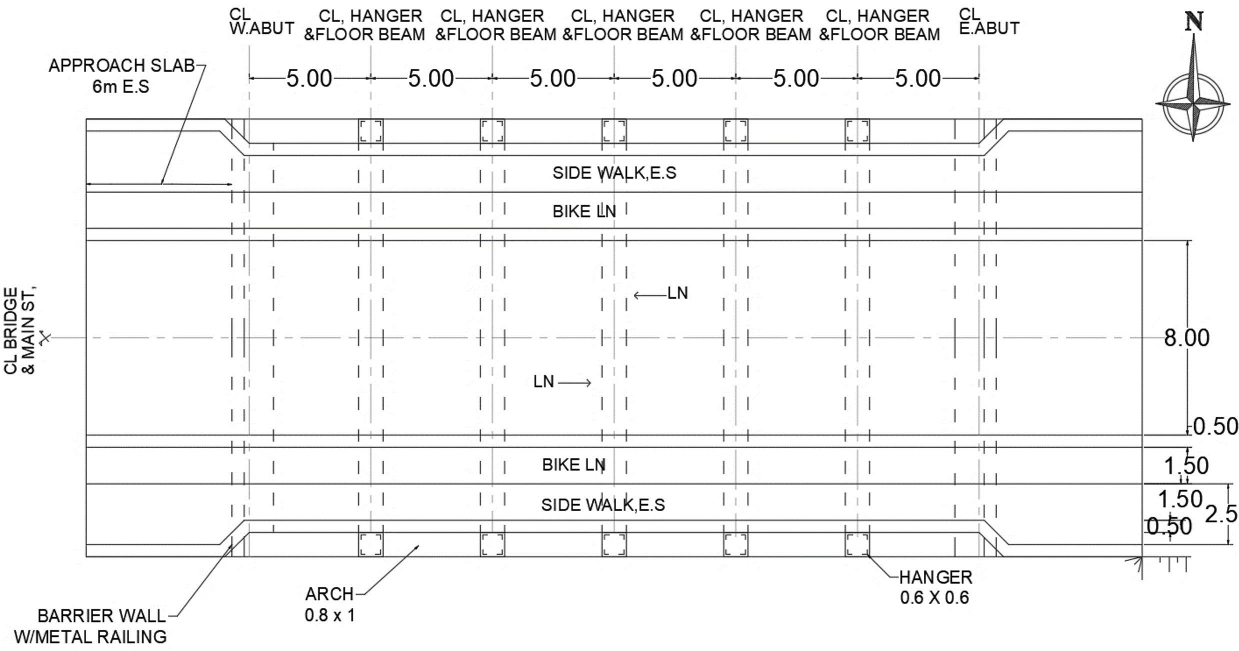

Figure 4: Alternative I Plan (Meters Unit)

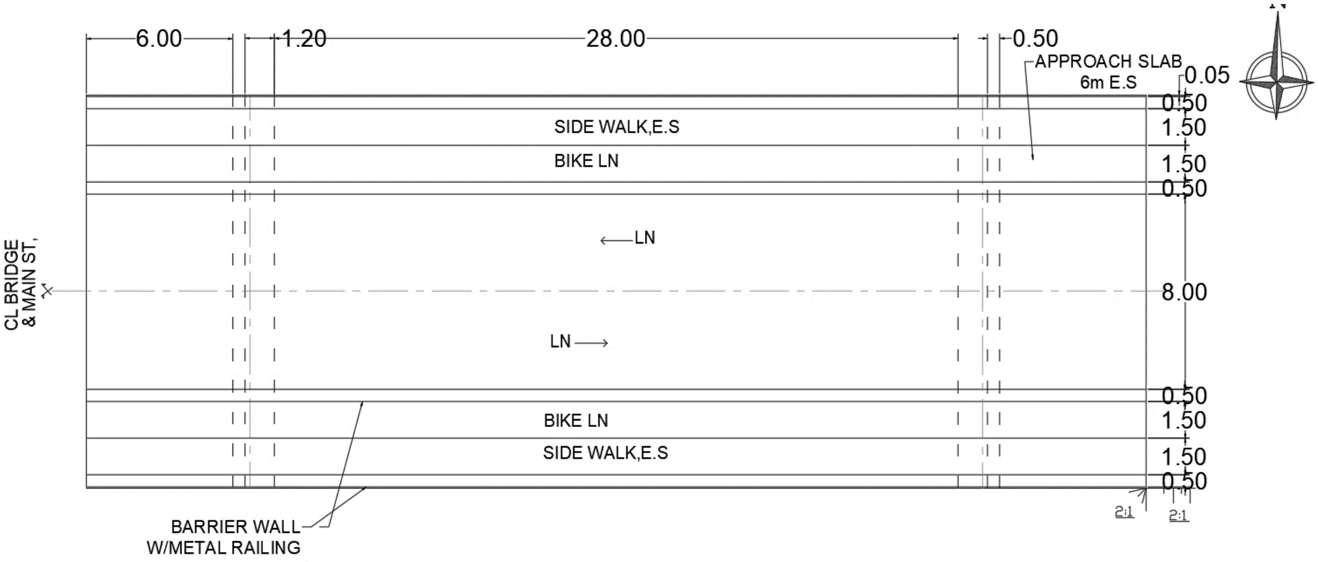

Figure 5: Alternative II Plan (Meters Unit)

2 CONCEPTUAL DESIGN REQUIREMENTS

2.1 Optimization of Superstructure Design

While discussing and comparing the two alternatives, the following factors were considered:

- Direct costs: salary/wages, materials, tools, transport, consultants etc.
- Indirect costs: traffic delay and diversion costs while the bridge is under maintenance/repair, bridge re-built, casualty costs etc.
- Durability: higher quality curing/pre-stressing environment results in a longer life for the bridge.
- Aesthetics: the alternative that is the most pleasing and best fits with its surrounding environment.

- Sustainability: materials to be chosen based on how eco-friendly they are and how much it can be recycled and reused in the future.

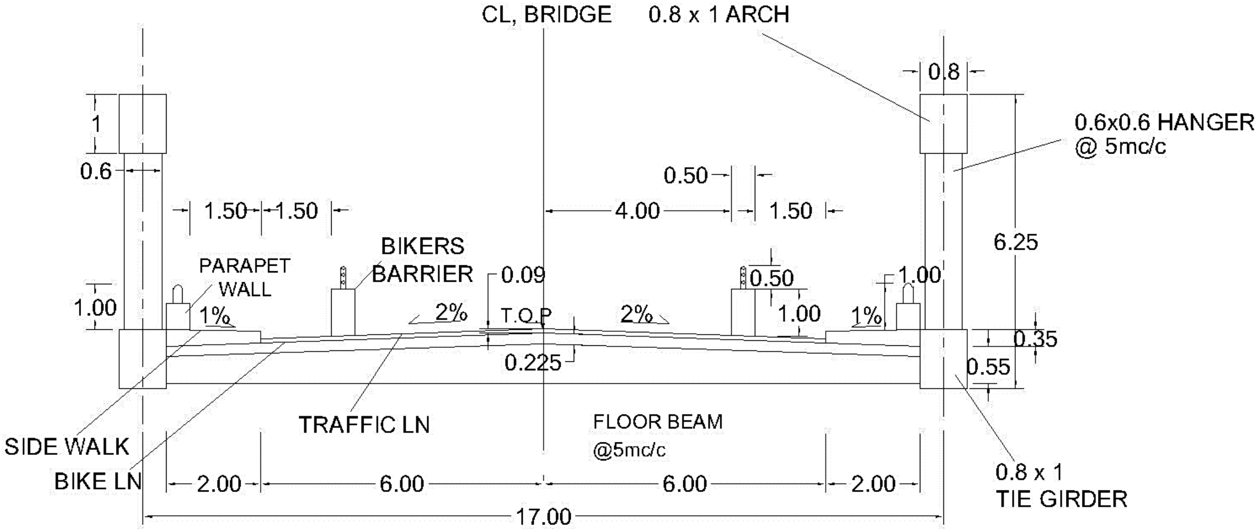

Figure 6: Alternative I X-Section (Meters Unit)

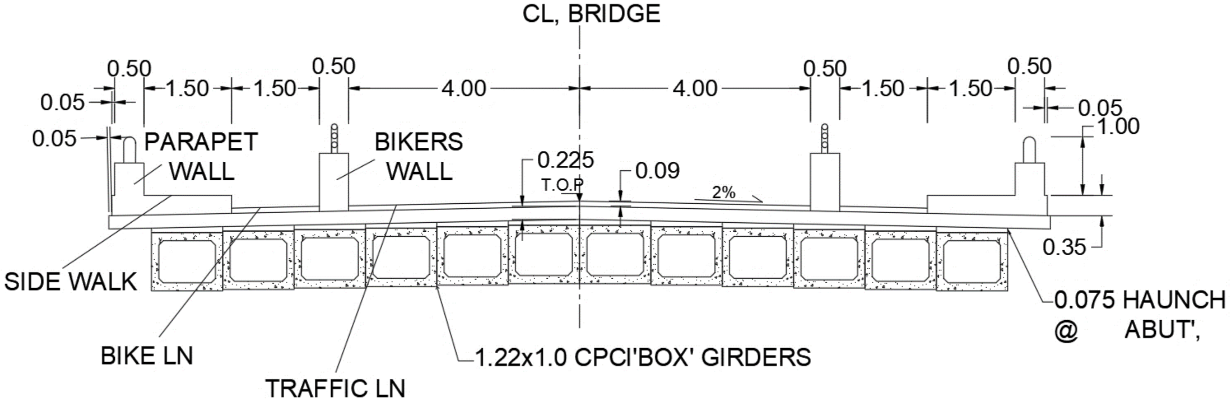

Figure 7: Alternative II X-Section (Meters Unit)

2.2 Consideration of Construction Staging

2.2.1 Substructure (same for both alternatives)

- Stage 1: Steel H-piles are driven and subsequently the footings are constructed.
- Stage 2: Piers, abutments and any other components of the substructure are established.

2.2.2 Alternative I

- Stage 3: Building a temporary shoring/formwork platform over the water stream without interrupting the navigational traffic.
- Stage 4: Constructing the tie girders and floor beams.
- Stage 5: The concrete deck is subsequently constructed.
- Stage 6: The tie girders are post-tensioned (details are in sec. 2.3)
- Stage 7: Barrier walls, sidewalks and wearing surfaces (waterproofing and pavement) are built.

2.2.3 Alternative II

- Stage 3: Installation of the pre-casted/pre-stressed box girders on top of the substructure.

- Stage 4: Construction of the slab deck and thereafter the barrier walls and sidewalk are built.
- Stage 5: Laying of the wearing surface (water proofing and pavement).

2.3 Introduction of Post-Tensioning System

Post-tensioning concrete is a variant of pre-stressed concrete in which tendons are stressed after the concrete has been placed and gained enough strength at the construction site (Poon, 2009). This technique will be used during the construction of the arch bridge, more specifically during the construction of the tie girders. When the tie girders are about to be constructed, ducts along with any reinforcement's bars are positioned in the formwork. Concrete is then poured and left until it has gained enough strength. Tendons consisting of seven high strength steel wires, are inserted into the ducts and are tensioned using mechanical jacks. The tendons are then anchored with the deck to induce pre-compressive stresses in the tensile stress regions of the tie girders, and the ducts are un-grouted for (unbounded tendons system). For the bonded tendons system, the ducts are grouted to act compositely with the deck and to provide corrosion protection for the tendons as well. This post -tensioning process to the tie girders will transpire when all the other structural members are fully constructed e.g. arch, slab, transverse beams etc. The advantages for such unique approach include:

- Overcoming tensile stresses to all members of the superstructure when loading is applied.
- Cracking is eliminated and deflection are minimized.
- Improving the durability of the bridge which in turn increases the service life of structure with minimum long-term repair/maintenance.
- This technique is also suitable for long spans (where the tendons can fit complex bridge geometry and site conditions) which increases range of application of structural concrete.

2.4 Introduction of Pre-Tensioning System

This type of method will be introduced during the construction of Alternative II. In this type of system, at the precast concrete plant, high strength steel strands are tensioned against the formwork before the concrete is poured (Poon, 2009). The concrete is then poured and left until it has reached its sufficient strength. The steel strands are then cut, and the tension force is released. The strands will immediately try to shrink to their original position but because there is a harden concrete bonded to the strands, the strands are unable to return to its initial position. Consequently, compression forces are induced in the concrete and when the strands are offset from the C.G. of the members, the member deflects upwards (i.e. introduce a camber). Thereafter, when the service loads are applied, the upward camber will balance the downward deflection/loads and increase beam capacity (Poon, 2009). The advantages for this type of pre-stressing include but not limited to,

- Tensile cracking is eliminated/ durability is improved for girders only and deflection is minimized.
- This technique is suitable for short spans and simple geometry where the girders need to be of standard sizes and shipped to site (limiting the size, shape and weight of girder).

3 MODELING AND ANALYSIS

3.1 General

The bridge structures were designed for combination of different types of specified loads resulting from vehicular traffic, the environment and the dead weight of the structure. These specified load types include dead, live, wind, temperature loads and earth loads. The design of the various loading criteria were done in accordance with the Canadian Highway Design Bridge Code (CHBDC).

3.2 Loads

3.2.1 Permanent Loads

3.2.1.1 Dead Load

Dead loads include the self-weight of the entire structure such as beams, arch girders, hangers, box girders etc.

3.2.1.2 Superimposed Dead Load

Superimposed dead loads were applied as non-structural elements which included but not limited to sidewalks, barriers walls, and wearing surface.

3.2.1.3 Earth Pressure

Typically, an abutment wall is backfilled with a granular material. Such backfill produces considerable pressure on the abutments and so these pressures were taken into account during the design process. A compaction surcharge was also included in the lateral earth pressures for the abutments as per the CHBDC.

3.2.2 Transitory Loads

3.2.2.1 Live Load

For both superstructure alternatives, a CL-625-ONT truck and a CL-625-ONT lane were applied as a vehicular traffic load as per the CHBDC guidelines. The dynamic load allowance (DLA) was considered for ULS and SLS load combinations.

3.2.2.2 Temperature

The maximum and minimum daily temperatures for the summer and winter respectively were selected to analyze the expansion and contraction of the both superstructures. These temperatures were also modified based on the type and depth of the superstructure. In addition, a temperature gradient for the summer and winter were applied to obtain the envelope of the temperature effect.

3.2.2.3 Wind Load

The wind pressure was applied to the structures both horizontally and vertically simultaneously. The vertical wind was considered to act either upwards or downwards. Moreover, wind pressure on the moving vehicles were also considered along the exposed surface of the design truck.

3.3 Load Combinations

The bridge superstructures were analyzed for both serviceability and ultimate limit states considering both maximum and minimum values of load factors. The loading combinations were studied independently to determine which combination would cause the greatest adverse effect on the superstructures. Using the software SAP2000 (Computers and Structures Inc, 2014), the most critical load combination for the bow-string arch bridge was found to be in ULS1 at the maximum load factor. The moment and shear diagram for the ULS1 load combination is presented in Figure 8 and 9. As shown in the diagrams, the moments and shears are greatly less than that of a conventional straight bridge. This is because the loads are transferred from the transverse beams to the tie girders as concentrated loads. The hangers that connect the arch and tie girders as a composite section with bottom flange (tie girder) and top flange (arch) transfer the concentrated loads to the arch. Hence, the bending moment produce thrust in the arch which will get distributed along the arch as a compression and gets balanced by tension in the tie girder. As a result, the local moments in the tie girders and arch are much lower than a conventional bridge. Also, the post-tensioning in the tie girders plays a big role in the in the reduction of the shears and moments. A post-tensioning force of around 2100 kN was applied to each post-tensioned tie girders with the purpose of introducing pre-compression to the entire structure resulting in lower moments and shears.

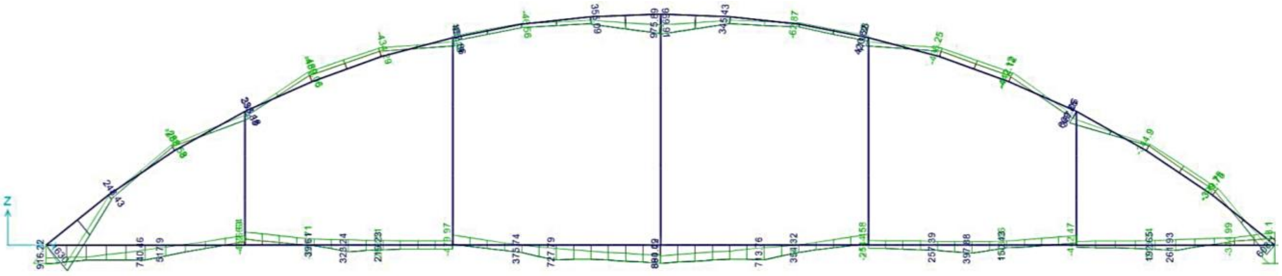

Figure 8: Alternative I Moment Diagram for ULS1 Maximum Load Factor (kN.m)

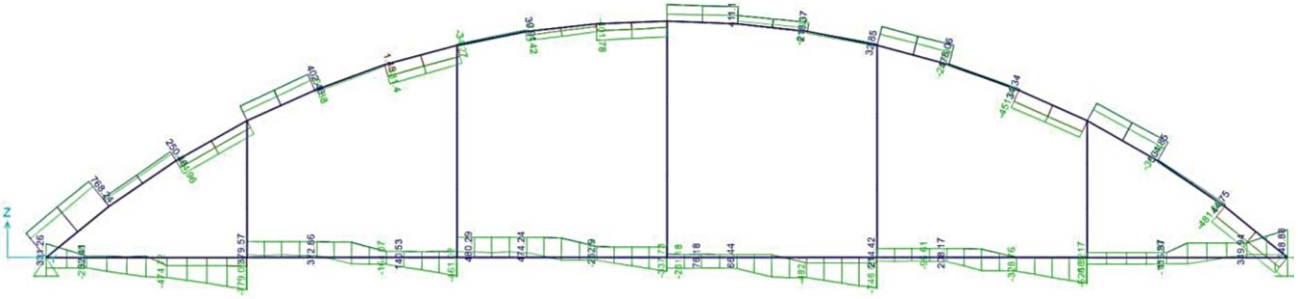

Figure 9: Alternative I Shear Diagram for ULS1 Maximum Load Factor (kN)

4 DESIGN

4.1 Flexural and Shear Design

The moment resistance for both alternatives were calculated as per the requirements given in the CHBDC and the values were compared with the maximum factored moments obtained from SAP2000 to ensure the adequacy of the designed sections. The maximum moments obtained were at the mid-span for both bridges since both bridges are of a single span type. These results are presented below in Table 1. Based on the values obtained above, a cross section of a single post-tensioned tie beam was selected for alternative I for design. As shown in Figure 10, a 6-33.7 mm diameter ducts with 3 strands in each duct were obtained. Stirrups and horizontal reinforcement were also used to accommodate the shear forces and to provide extra moment resistance. The factored shear resistance, V_r for both options were also calculated. The maximum factored shear forces, V_f, obtained were at the effective depth, dv, distance from the face of supports (Table 2). Both alternatives seem to have almost the same shear force.

Table 1: Factored Moment and Moment Resistance for Both Alternatives

	Maximum Factored Moment (M_f) (kN.m)	**Moment of Resistance (M_r) (kN.m)**
Alternative I	880.7	1942.7
Alternative II	6359.0	6459.0

Table 2: Factored Shear and Shear Resistance for Both Alternatives

	Maximum Factored Shear (V_f @ d_v) (kN)	**Shear Resistance (V_r) (kN)**
Alternative I	469.5	690.7
Alternative II	648.3	11999.0

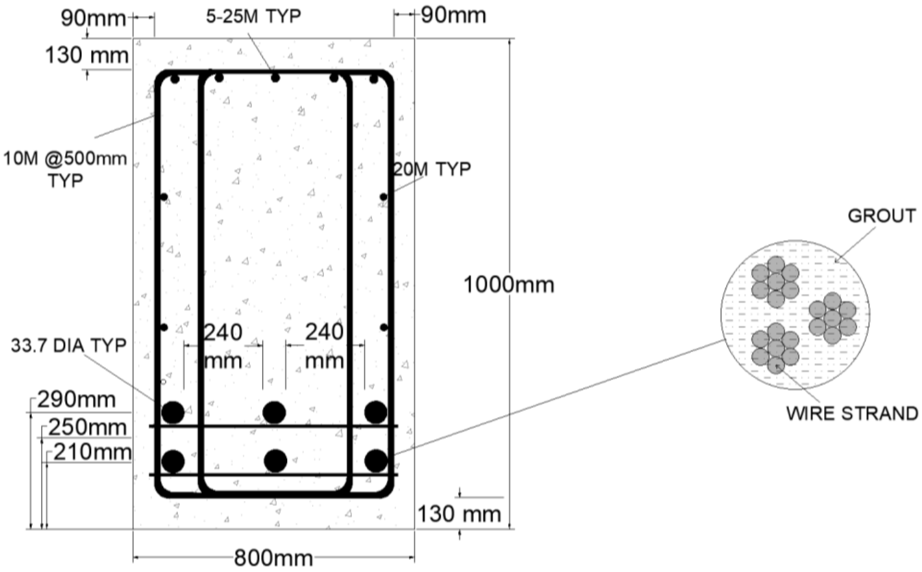

Figure 10: Cross Section of Post-Tensioned Tie girders (Alternative I)

4.2 Superstructure Comparison

Many factors were taken into account when comparing both alternatives. The figure below shows the cost break down for each alternative. Note, the costs shown below represent only the component of the superstructures that are different from each other (e.g. box girders, arch girder, transverse beams etc.). Slab decks, wearing surface, barrier walls, and substructure/foundations were not included in the cost comparison as they can be reasonably assumed identical and have negligible impact on the cost difference.

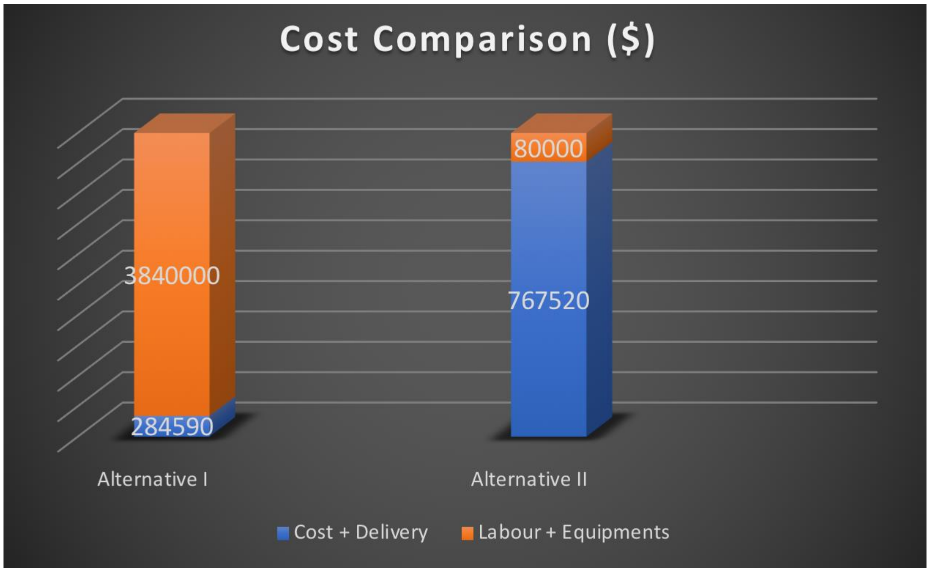

Figure 11: Break Down Cost Comparison for Both Options

As shown in Table 3, each alternative was compared based on cost, durability, construction impact, aesthetic appeal and inspection difficulty. Weighted scoring model was implemented to give each alternative criteria score. The highest scoring option is awarded the chosen alternative. The weight (%) is assigned based on the focal points of the projects. The weight of each criteria is chosen after the preferences of the client. The total is presented, revealing that alternative I has a bigger value in weight than alternative II and therefore, the arch bridge is the chosen bridge for this project.

Table 3: Comparison between Alternatives

Criteria	Weight (%)	Alternative I (Points/10)	Alternative II (Points/10)	Reasoning
Cost	15	3	8	A1 is more cost efficient than A2.
Aesthetics	45	10	4	Due to A1's complexity and exuberance it is a more aesthetically pleasing bridge.
Sustainability	10	4	7	A2 is more sustainable because it is made of pre-cast concrete, while the arch bridge is made of in-cast concrete.
Durability	10	8	5	A1 has more durability due to the effect of post-tensioning
Inspectability	10	10	2	A1 has a more environmentally exposed components, making it more inspectable than A2.
Ease of Construction	10	2	9	Due to its higher degree of simplicity, A2 is easier to construct.
Final Score	100	7.35	5.3	-

Note: Alternative I is referred to as A1 and Alternative II is referred to as A2.

5 CONCLUSION

This paper presented the comparison between two superstructure alternatives; a bow-string arch bridge and a side-by-side CPCI Box Girders. The main focus in the comparison between both structures was to design an aesthetically pleasing bridge with enough strength, safety and durability while presenting a cost-effective solution. Located in the Greater Toronto Area (GTA), the chosen bridge would have pedestrian/bikers/vehicular traffic passing over a water stream surrounded by a scenic valley/woods. Throughout the project, the following remarks were noted:

- Because of its graceful and curvy appearance, the bow-string arch bridge was considered a more aesthetic pleasing alternative.
- The structure of the bow string arch bridge is exposed and easier to inspect and identify any problems compared to the side by side box girder bridge, which will facilitate/reduce the maintenance in the long term.
- The post-tensioned system applied to the arch bridge will help controlling the cracking, deformation and stresses induced in the entire superstructure. Therefore, the durability and appearance will be significantly improved.

Considering all the aspects presented in this paper, the final decision is to select the bow-string arch bridge as the chosen alternative.

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