AN INNOVATIVE ACCELERATED BRIDGE CONSTRUCTION APPROACH INCORPORATING PRECAST PANELS, FIBRE-REINFORCED POLYMERS BARS AND ULTRA HIGH PERFORMANCE CONCRETE

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Abstract: The need for enlarging the extents and capacity of existing transportation structures has been growing rapidly worldwide during the past decade. Meantime, minimizing the impact on traffic and shortening the construction duration pose significant challenges to jurisdictions, engineers and contractors. This paper presents a project for widening an existing two-lane bridge over a major water stream within the Great Toronto Area (GTA). Two additional lanes are needed to improve the vehicular traffic flow of the road crossing the water stream. The subject bridge and its proposed widening are of a semi-integral abutment type. This type of bridges is characterized with high durability of both superstructure and substructure components. Two deck systems utilizing Steel I-girders and Steel Box-girders were examined in order to achieve an optimum bridge design. Some of the various challenges were to maintain the existing bridge functional during construction and to keep the water stream beneath flowing free of any falling debris. Further, high durability measures were considered for the widening structure along with a reduction of the construction schedule within a reasonable budget. Therefore, the design/construction criterion focused an innovative accelerated construction approach in order to satisfy such challenging demands. Through such approach, a deck system of precast concrete panels reinforced with Glass Fibre-Reinforced Polymers (GFRP) bars and jointed, on site, with Ultra High Performance Concrete (UHPC) is proposed. The proposed construction methodology, complemented by such advanced construction materials, accommodates the technical and financial measures of the project from both short and long term aspects.

Key words: Bridge, FRP, UHPC, Precast Panels, Accelerated construction.

1.0 Introduction

1.1 Project Description

The travel throughout the Greater Toronto Area (GTA) has become a prevalent issue, especially with the surge in the number of commuters. Many existing arterial roads, highways and bridges are unable to sufficiently accommodate the high volume of traffic during peak hours of travel resulting in an increase of both traffic congestion and commute times. This growing demand is met by new infrastructure additions as well as expanding/widening the existing transportation structures. During such projects, the priority is to complete the construction in the shortest possible duration. The subject project proposes widening of an existing bridge which spans over a water stream located by Highway 404 in Toronto, with the intent of increasing the flow of vehicular traffic in the North-South direction of the bridge. This widening is intended to accommodate an additional two lanes which will benefit the commuters as the bridge can carry more traffic, resulting in a shorter commute time. Rapid construction techniques are highly recommended due to a major water stream flowing below the bridge and the construction taking place while the two current lanes are still operational.

1.2 Bridge Description

The existing bridge is a 40 m single span superstructure supported by a roller and a hinge at the South and North abutments respectively. The bridge consists of two vehicular traffic lanes (one lane per direction of travel) both 3500 mm in width as well as 500 mm shoulders and 500 mm barrier walls on each side for a total width of 9000 mm in the cross section. By widening the existing bridge, an additional two lanes with a width of 3500 mm each will be created to allow for a more efficient and sustainable flow of vehicular traffic. The figure below illustrates the plan view of the existing bridge.

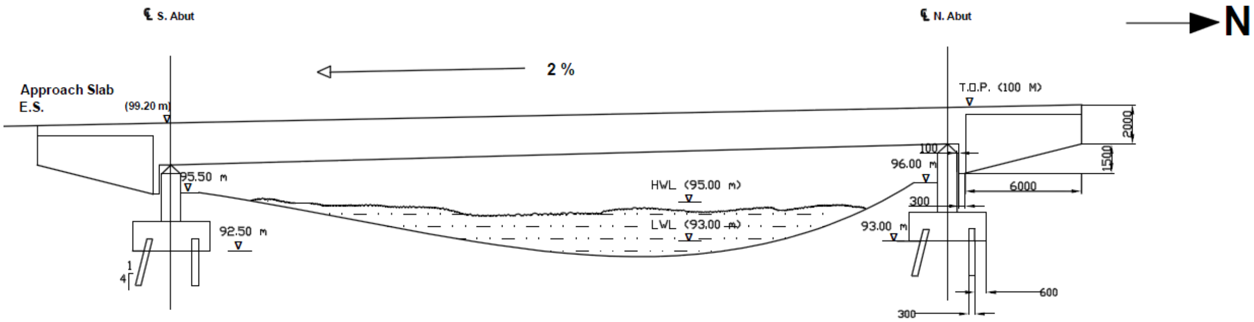


Figure 1: Elevation of the existing bridge (dimesnsions are in mm)

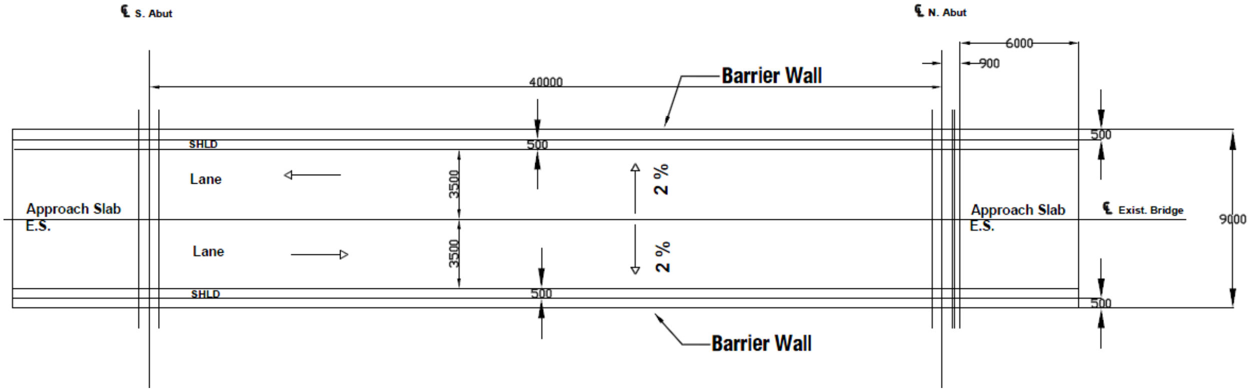


Figure 2: Plan view of the existing bridge (dimesnsions are in mm)

The bridge under consideration for this project is semi integral in configuration. It has no joints and spans from one abutment to the other abutment without any movement in the deck. At each end of the semi-integral bridge, there is a vertical extension of the deck slab otherwise known as the ballast wall which undertakes the active soil pressure acting on the superstructure. Consequently, the bridge expansion joints are relocated within the approach zones. Any possible leakage of water/de-icing salts through a deteriorated expansion joint in the future shall not attack within the envelope of the superstructure. Therefore, such structural system provides significant protection for the bearings, superstructure and substructure components, i.e. an overall high durability measures of the bridge. The addition of the widened section will be separated by an expansion joint to absorb vibrations and allow movement caused by thermal expansion between the two bridge sections (Hussain and Bagnoriol 1999).The piles for our bridge were assumed to be driven into the bedrock stratum. Based on the data collected from a geotechnical analysis of the granular backfill we determined the bearing capacity of the soil. A 2 metre layer of backfill was used to counter frost damage to the substructure.

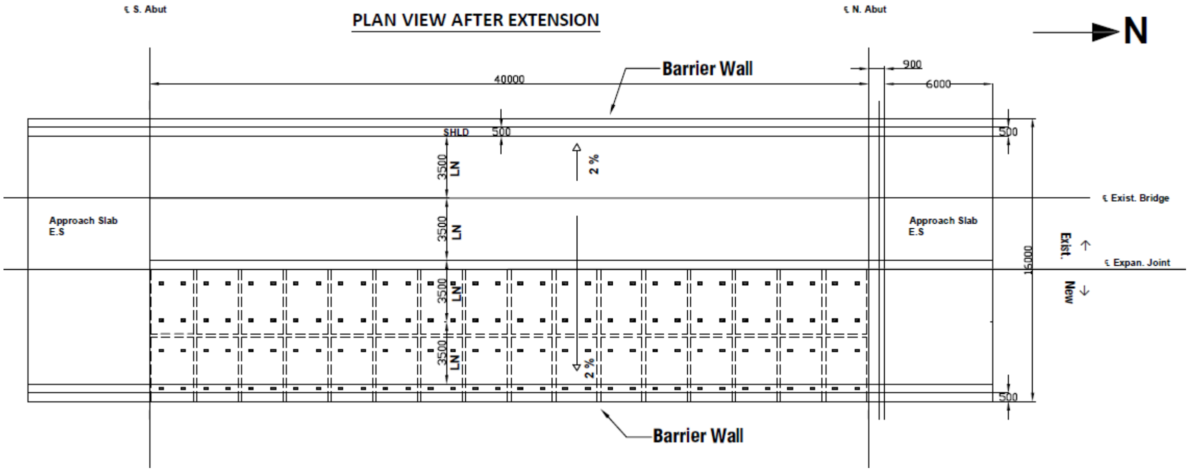


Figure 3: Plan view of the widened bridge (Dimesnsions are in mm)

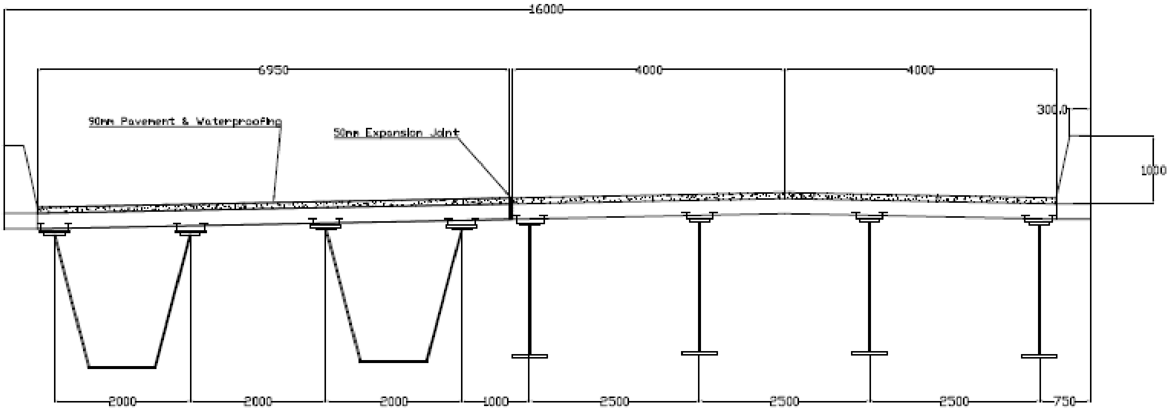


Figure 4: Cross Section of the widened bridge (Dimesnsions are in mm)

1.3 Proposed Construction Approach

An accelerated bridge construction implements new technologies such as the use of pre-casted slabs along with Ultra High Performance Concrete in order to shorten the time of construction and minimize indirect costs. The durability and performance level of the structure are further enhanced by the implementation of GFRP reinforcement due to its unique non – corrosive nature and high weight to strength ratio (CSA-807-10, 2010). This approach reduces the construction period of the superstructure by four weeks.

1.4 Scope of Work

The main objective of this study was to determine the most favourable superstructure type for the widening of the bridge while meeting the specified requirements of the Canadian Highway Bridge Design Code (CHBDC 2006). To choose the most efficient and effective design of the bridge, two options for the girders and two options for the deck slab were considered. The girder options considered the use of steel box girders and steel I girders. Also, two options for the deck slab were considered; cast-in-place concrete and precast concrete panels, both of which would have glass fiber reinforced polymers (GFRP) bars as the concrete reinforcement.

2.0 Conceptual Design Requirements

2.1 Optimization of Superstructure Design

The steel girder options (I-girders and Box girders) chosen to be investigated for the bridge were assessed based on several key factors. These factors were including and not limited to:

- Direct costs such as manufacturing, erecting, labor and maintenance costs;
- Indirect costs such as costs associated with longer construction period;
- Increasing durability and structural strength by ensuring proper curing conditions and high quality materials which in return increases the service life;
- Appearance and aesthetic aspects;
- Sustainability in terms of implementing a more eco-friendly option; and
- Elimination of any possible tasks (i.e. casting-in-place and use of framework) which can cause stream contamination.

2.2 Consideration of Construction Staging

During the construction phase, the existing bridge will remain open and carry local traffic. Therefore, a scheme of construction sequence was proposed as follows:

- First stage; the piles, footings and substructure components of the widening will be constructed;
- Second stage; the barrier walls on the east side of the existing bridge will be removed as well as the top part of the wing walls underneath these barrier walls within the approach slab zones. An expansion joint with a width of 50 mm will be introduced along the bridge to separate between the new (widening) and existing superstructures;
- Third stage; the new girders will be installed and the concrete deck will be constructed; and
- Fourth stage; the construction will be completed by the implementation of the waterproofing system, pavement and barrier wall of the widening.

2.3 Introduction of High Durability

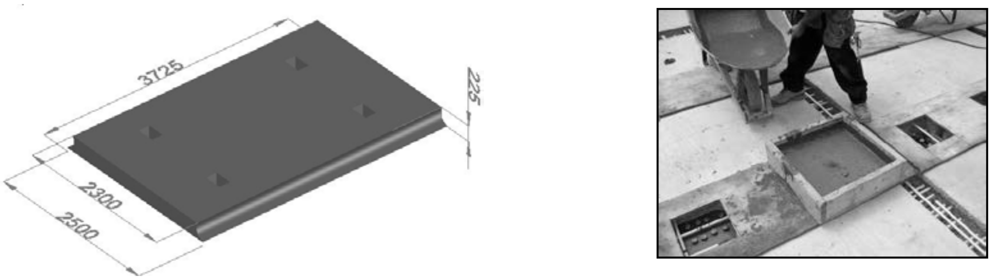
In regards to the bridge deck slab and barrier walls, glass fiber reinforced polymer (GFRP) bars were selected as concrete reinforcement. GFRP bars are known for their non-corrosiveness and high strength to weight ratio. The implementation of such bars brings forth many advantages such as high durability and less deterioration. Consequently, this will reflect on a significant reduction of the direct costs for repair/maintenance compared to those required due to steel corrosion issues. Further, this avoids the indirect costs associated with partial (or full) closing of the bridge for future repair and/or full replacement of steel-reinforced concrete decks and/or barrier walls. The use of GFRP in precast slab panels and barrier walls in similar projects is shown in Fig. 5.

Figure 5: GFRP in precast panels and barrier walls (Young et al. 2012)

3.0 Accelerated Bridge Construction

3.1 Precast Concrete Panels

The proposed option for construction of deck slab is to use precast concrete panels which reduce the formwork time during construction substantially while the significant curing time for concrete is completely eliminated. Additionally, the production of precast panels receives high measures of quality control as they are constructed in the factory under optimum conditions. These panels will be placed in two rows of 16 on the widened portion of the bridge for a total of 32 panels. The pre-casted slabs are placed 200mm apart and joined using ultra high performance concrete (UHPC) on-site. Pockets will be introduced in the panels during production to accommodate the shear studs of the girder top flange. The pockets will be filled with UHPC on-site as well. The dimensions of each panel as well as the detail of their joints are shown in Fig. 6.



a) Dimensions (mm) b) Shear studs pockets and joints (Yong et al. 2012)

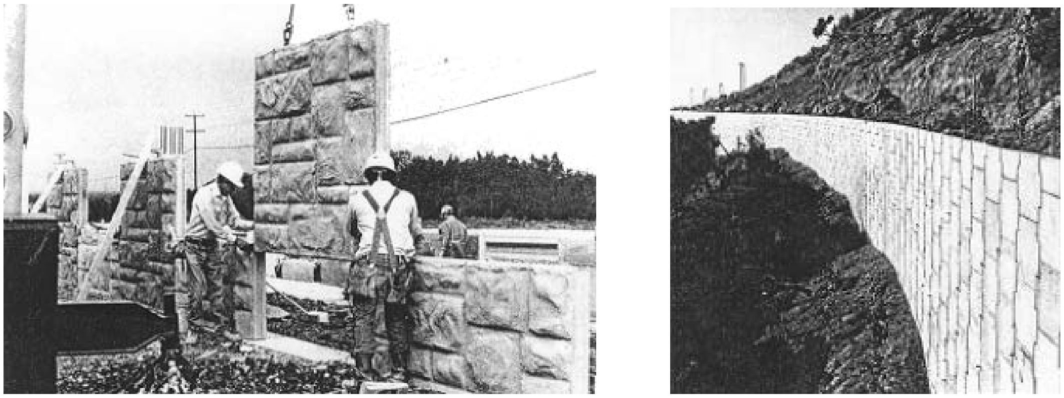
Figure 6: Precast Concrete Panels

3.2 Ultra High Performance Concrete (UHPC)

The use of ultra-high performance concrete, with its significantly shorter curing time (around few hours), suits the accelerated bridge construction approach. Also, UHPC products can provide high resistance; i.e. over 100 MPa in compression and over 20 MPa in tension; (Lafarge 2009) that is multiple times greater than that of conventional concrete. The main reason is the utilization of metal fiber reinforcement in the concrete mix that enables the concrete to withstand extreme tensile/bond stresses without failure. Such strength was a major key to achieve a substantially reduced lap splice (around 150-200 mm) for the GFRP bars at the panel joints (Fig. 5). Further, the low permeability of UHPC provides more durable and stronger joints which significantly reduce the repair/maintenance costs throughout the life cycle of the bridge.

3.3 Prefabricated Retaining Soil System (RSS)

The prefabricated retaining wall system, known as mechanically stabilized earth, MSE, (National 2001) or retaining soil system, RSS, is proposed along the East side of the widening. RSS system is considered one of the most common soil retaining systems used for accelerated/optimum cost construction. The system is constructed by excavation that is performed near the abutment. The excavated portion is then filled by a small layer of backfill (around 300-500 mm lifts) and compacted. Geotextiles (ties), anchored to the wall panels, are then placed on the compacted backfill where the soil active pressure is exerted on the panels and resisted by the tie (tension) reaction. The process of filling, compaction and laying of geotextiles (ties)/panels are repeated until the whole excavated trench is filled. Moreover, RSS wall systems are characterized with high durability and aesthetics standards. Example of projects utilizing RSS walls is shown in Fig. 7.



a) During construction b) After construction

Figure 7: RSS wall system (National 2001)

4.0 Modelling and Analysis

4.1 General

The structural loads, analysis and design of the bridge components are in accordance to the Canadian Highway Bridge Design Code (CHBDC 2006) for the design truck CL-625-ONT. The following assumptions were considered in the modelling and analysis: (i) two and three dimensional FEM was utilized for the structural analysis, i.e. summing the properties and loads of the bridge cross section, and (ii) seismic activities were neglected as per the bridge site and characteristics (CHBDC 2006).

4.2 Loading Cases

4.2.1 Live Load

The vehicular traffic loads were applied and analysed in accordance with the CHBDC guideline using a CL-625-ONT truck. The loads take into account lane loads and dynamic load allowances as impact loads based on the number of truck axles for each loading condition as per the CHBDC.

4.2.2 Dead Load and Superimposed Dead Load

The overall structure of the composite bridge creates two permanent loads on itself known as the dead load and the superimposed dead load. The dead load is created by the weight of the superstructure which is comprised of the structural components, the deck slab and steel girders. The superimposed dead loads are formed by dead loads placed on the superstructure after the main structural components of the bridge have been constructed. These include the shoulders, barrier walls and the wearing surface.

4.2.3 Temperature Load

Due to the varying temperatures throughout the year in Toronto, Ontario, it is necessary to determine the effect of temperature change on the composite bridge. A temperature of 15^{o}C was assumed to ensure optimal conditions during the concrete slab and steel girder installations. In addition, a maximum temperature of 45^{o}C for the summer, a minimum temperature of -25^{o}C for the winter and a temperature gradient of 30^{o}C for the deck slab was used to analyze the expansion and contraction of the superstructure.

4.3 Loading Combinations

The bridge superstructure was analysed at its ultimate limit state in accordance with CHBDC standards. Since the bridge has a single span it was subject to the relevant maximum and minimum ULS load factors in order to design for its critical condition. The geometry of the bridge results in a wind load being applied to the exposed area of the superstructure. These loads are transferred from the superstructure through a rigid diaphragm placed at each of the abutment to the bearings at the supports which in turn transfer them to the bridge substructure. The transverse reaction from wind loading is used to design the transverse resistance of the bridge bearing and assists in determining the required number of piles given the maximum pile capacity to resist horizontal loading on the structure. Using the software, SAP2000, the superstructure along with the loading cases stated above, was modelled and analysed in order to obtain an envelope of its straining actions (Moment and Shear) to study the effect of the applied factored loads. Figures 8 and 9 illustrate the bending moment and shear obtained from the performed analysis on the superstructure. In addition, a three dimensional model was also analysed using a finite element analysis through the CSI Bridge software (Fig. 10). A three-dimensional finite-element model was used to analyze the composite bridge in this study. The model was comprised of the superstructure with corresponding hinge and roller supports at the abutments. The superstructure was divided into a concrete deck slab, steel top flanges, steel webs, and steel bottom flanges for the girders. The components were modeled using four-node shell elements with six degrees of freedom at each node. The finite element model connects the concrete deck nodes above the steel top flanges to the corresponding nodes within the flange to ensure composite action between the concrete deck and the steel girders.

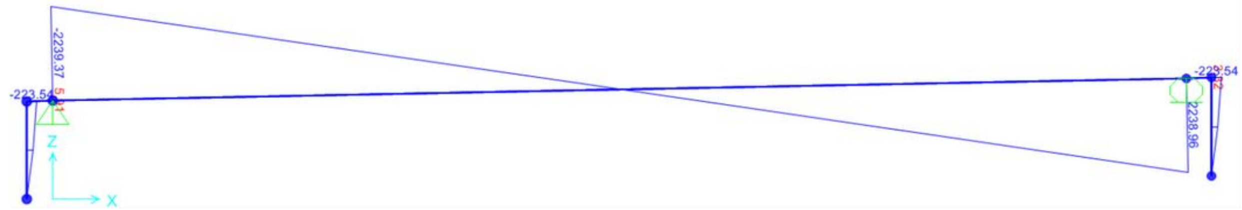


Figure 8: Shear Force Diagram for Box Girder

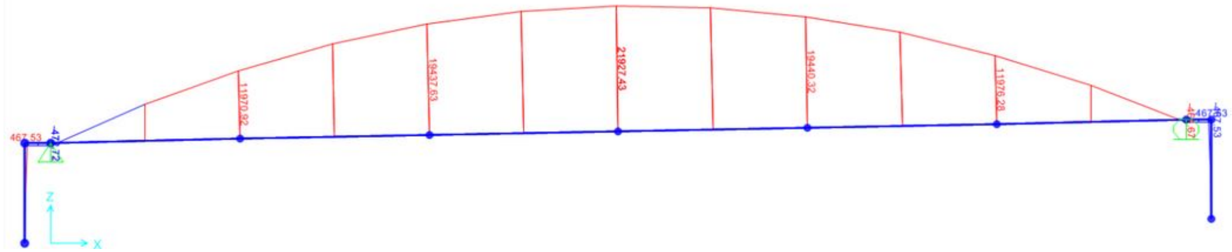


Figure 9: Bending Moment Diagram for Box Girder

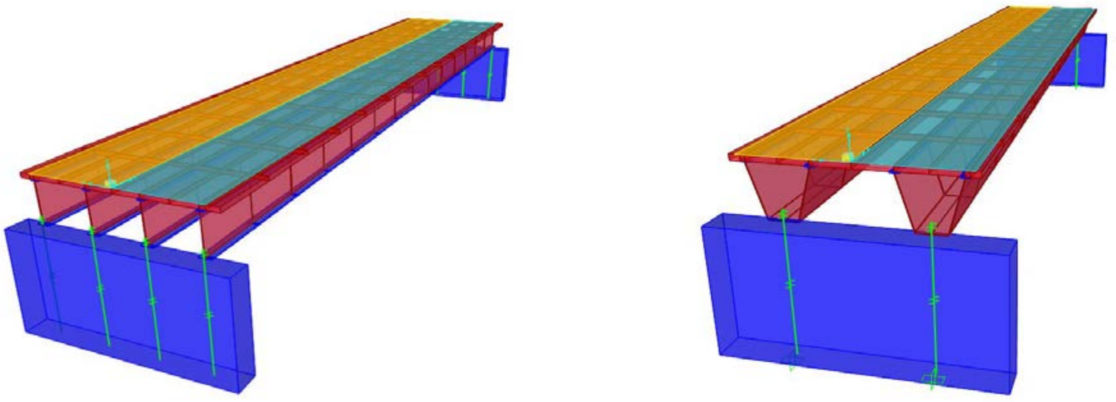


Figure 10: isometric view of the 3D-FEM of the existing bridge (left) and the widening (right)

5.0 Design

5.1 Girder Flexural Design

The moment resistance for the superstructure was calculated in accordance with the Canadian Highway Bridge Design Code (CHBDC), and the values were subsequently compared with the maximum factored moments obtained using SAP2000 software, to ensure its compliance with the code. These results are summarized in Table 1. The steel bridge girder and concrete slab were designed as a composite section throughout the span of the bridge.

Table 1: Comparison of Moment Resistance and Factored Moment

	Maximum Factored Moment (M_f) (KN·m)	**Maximum Moment Resistance (M_r) (KN·m)**
Steel I Girder	9508	28786
Steel Box Girder	21927	43063

Therefore, designed shear studs shall be implemented in order to guarantee a non-slip interface between the girder top flange and the base of the concrete slab. As seen from the values listed in Table 1, the resistance moments, for both girder types, exceed the corresponding factored moments. Therefore, it can be concluded that the resisting capacity of the proposed Steel I girders and Box girders are adequate to sustain the applied factored positive and negative moments.

5.2 Girders Shear Design

The shear resistance is provided primarily by the webs of the steel girders. The factored shear resistance of the web for the I-girder and the box girder were calculated in accordance with clause 10.10.5 of the CHBDC. The maximum shear force can be found at the supports of the deck for both options. A comparison of the factored shear and shear resistance of the two girder alternatives show the adequacy of both alternatives. The values are summarized in Table 1 as shown above.

Table 2: Comparison of Shear Resistance and Maximum Factored Shear

	Maximum Factored Shear (V_f) (KN)	**Maximum Shear Resistance(V_r) (KN)**
Steel I Girder	4798	973
Steel Box Girder	16070	2239

6.0 Girders Options Comparison

During the design phase, two girders options were analyzed; steel I girders and steel box girders. The advantages and disadvantages for each girder option are outlined in Table 3 and Figure 9. The decision was based on factors such as durability, installation, costs and aesthetics. Although the fabrication costs of the box girders are more expensive than I girders, only two box girders are needed compared to four I girders. The total weight of the box girders are also less, resulting in a lower cost for box girders. Total costs for manufacturing and transportation for I girders would be $396,203.45 whereas for box girders would be $319,997.75, outlined in the figure above. Box girders also have a longer service life which reduces future maintenance costs.

Table 3: Comparison between I girders and box girders

Steel I girders	Steel Box girders
Advantages	
▪ Easy to fabricate/transport ▪ Easy to maintain and rehabilitate	▪ High structural capacity, especially for torsion ▪ High aesthetics standards
Disadvantages	
▪ High corrosion exposure ▪ High repair/ maintenance cost	▪ Low accessibility for repair/maintenance

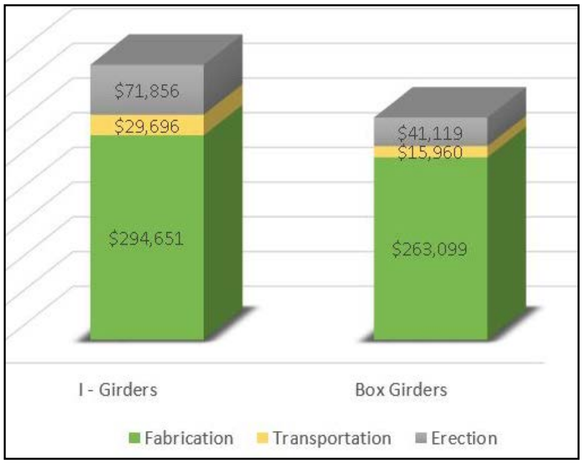


Figure 9: Cost comparison for girder options

7.0 Deck Options Comparison

With the design of the bridge decks, cast in place and pre-casted slab options were considered. For both options, glass fiber reinforced polymer (GFRP) bars are used for the top layer of reinforcement in the concrete. The advantages and disadvantages are shown in Table 4 and Fig. 10.

Table 4: Comparison for concrete deck options

Cast in Place	Precast Panels
Advantages	
▪ Easy to accommodate/ embed utility lines ▪ Conventional/ common construction ▪ Low production cost	▪ High structural capacity ▪ Short on-site construction time High durability ▪ Low maintenance cost
Disadvantages	
▪ Long on-site construction time ▪ Low durability ▪ High maintenance cost	▪ High production cost

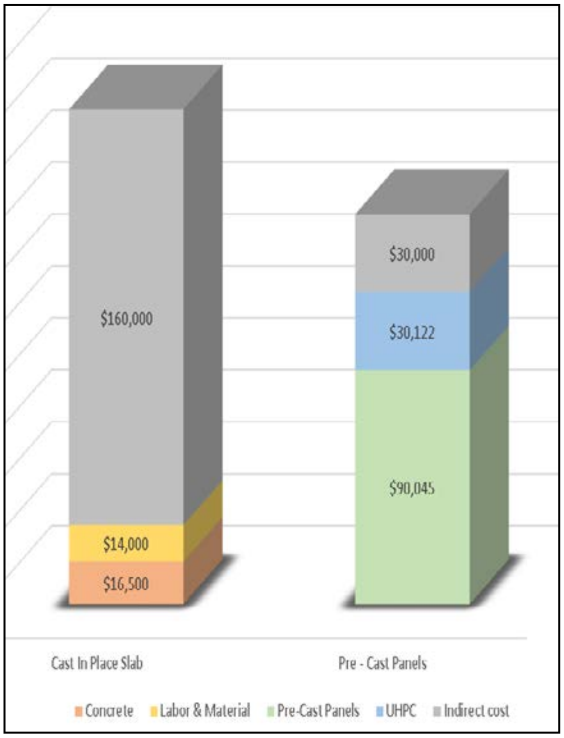


Figure 10: Cost comparison of deck options

Although the construction (initial) cost for cast in place concrete is $30,500.0 compared to $120,167.00 for precast panels, the precast option was more favourable. First, the construction period for the cast in place concrete is estimated to be over a month longer than that of the precast slab. Second, the high durability of the precast panels significantly reduces both the direct long term (repair/maintenance) costs throughout the life cycle of the bridge and the indirect coast associateed with bridge partial/full closure at each repir cycle.

8.0 Conclusions

The paper presents a design project for widening an existing semi-integral single span bridge located over a major water stream in the Greater Toronto Area (GTA), Ontario, Canada. The widening is designed to accommodate two additional lanes in order to reduce the amount of traffic congestion and commuting time through the bridge route. During the construction phase, the existing bridge should remain open and carry local traffic. In order to achieve the project objectives, the conducted design work can be concluded as follows:

- The bridge was modelled as a 2D-FEM through a preliminary design phase and was analyzed under the applied loads and loading combinations to meet the strength and serviceability requirements of the Canadian standards. Further refinement of loads, modelling and analysis was carried out through a 3D-FEM during the final/detailed design phase.
- Two steel girder options (I-girders and Box girders) and two concrete deck options (cast-in-place and precast panels) were evaluated to determine the optimal design solution for the superstructure.
- The box girders proved to be an optimum option for their high structural capacity, torsional resistance, minimum labour/time for on-site installation, high durability and high aesthetic standards.
- Precast panels were chosen for the concrete deck as they will reduce the construction time significantly and provide high quality and durability measures.
- An innovative approach for accelerated construction with high durability measures was proposed to incorporate the precast concrete panels, ultra-high performance concrete (UHPC), Glass Fibre-Reinforced Polymers (GFRP) bars and prefabricated walls as retaining soil system (RRS).
- The premium cost estimated to be spent over the implementation of these construction techniques and advanced materials is quite justified by over a month saving in the construction schedule as well as the high quality/durability of the bridge structure.
- Such high durability significantly reduces the direct (repair/maintenance) costs throughout the life cycle of the bridge. Further, it minimizes, or entirely eliminates, the indirect costs associated with partial (or full) closure of the bridge/detour scenarios as typically required for future repair/full replacement of bridge components constructed with conventional methodologies/materials.

References

Hussain, I., and Bagnoriol, D. 1999. Semi-Integral Abutment Bridges. Ministry of Transportation of Ontario (MTO), Head Office, Ontario, Canada.

CSA-807-10. 2010. Specifications for Fibre-Reinforced Polymers. Canadian Standards Association, Toronto, Ontario, Canada.

CHBDC. 2006. Canadian Highway Bridge Design Code. Canadain Standards Association, Toronto, Ontario, Canada.

Young, W., Boparai, J., Perry, V., Archibald, B., and Salib, S. 2012. Whiteman Creek Bridge - A Synthesis of Ultra High Performance Concrete and Fibre Reinforced Polymers for Accelerated Bridge Construction. Proceedings of the 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials, HiPerMat 2012, Kassel, Germany.

Lafarge North America. 2009. Product Data Sheet: Ductal® JS1000, http://www.ductal.com/JS1000_2009.

National Highway Institute-Office of Bridge Technology. 2011. Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines. U.S. Department of Transportation, Washington, D.C.