Rapid Bridge Replacement of Concrete Rigid Frame Structures: Case Study

Mohamed Zawam
Project Engineer
Stantec Consulting Ltd.
Waterloo, Ontario
Mohamed.Zawam@stantec.com

Trevor Small
Senior Associate
Stantec Consulting Ltd.
Hamilton, Ontario
Trevor.Small@stantec.com

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Abstract

A rapid bridge replacement (RBR) method was designed and utilized for the replacement of five overpasses along Highway 417 at Rochester Street, Booth Street, Percy Street, Preston Street, and Bronson Avenue in Ottawa. The current paper focuses on the replacement of the overpass at Bronson Avenue which involved the replacement of two rigid frame structures, supporting eastbound and westbound lanes (EBL and WBL), separated by a 20 mm expansion joint gap.

The existing concrete rigid frame structures were demolished in place while preserving the existing footings, with excavation being performed in parallel. The new structures were prefabricated in staging areas near the sites and transported to their final locations using specialized heavy-lift equipment, including self-propelled modular transporters (SPMTs). The new rigid frames were founded on top of the existing footings.

Several replacement alternatives were studied, including staged construction, rapid bridge replacement with a composite steel girder deck, and the construction of a secant wall behind the footings during nightly closures. It was concluded that the engineering and construction costs for a rigid frame RBR alternative is the lowest cost among feasible alternatives and had the least impact on traffic.

A three-dimensional, linear elastic finite element analysis was conducted to ensure the strength and stability of the structures during lifting, transportation, and final backfilled service conditions. This presentation discusses the challenges encountered during the design and construction of the structure and the solutions implemented to address them. The construction was successfully completed in July 2023.

Introduction

Background of Structure and Project

Morrison Hershfield (now Stantec) was retained by the Ontario Ministry of Transportation (MTO) to undertake a preliminary design and provide recommendations for the replacement of five overpasses on Highway 417 at Rochester Street, Booth Street, Percy Street, Preston Street, and Bronson Avenue. Included in the project was the rehabilitation/replacement of 23 retaining walls, replacement of noise barriers, as well as various road works. The current paper discusses the details of the replacement at the Bronson site only.

The Highway 417 overpass at Bronson Avenue was originally constructed in 1965 and consists of two (2) side-by-side concrete rigid frame structures with a clear span of approximately 23.8 m. The structures have a minor skew of 0° 19’ 0” and have a minimum vertical clearance of approximately 4.5 m. The reinforced concrete depth of the deck is approximately 838 mm at midspan, and 1555 mm at the face of the abutment wall. The abutment walls above footings vary in height while the thickness of stepped footing is approximately 914 mm.

The overpass was rehabilitated in 1980’s. These rehabilitations included adding approach slabs, installing barrier walls, replacing the asphalt and waterproofing, and placing a latex modified concrete overlay. All three structures need to be replaced.

The preliminary design study recommended that the existing structures be replaced with concrete rigid frame structures. The proposed structure was designed to span, at least, the same distance as the existing structures and provided a minimum vertical clearance of 5.1m. The road width at Bronson remained unchanged.

Various alternatives were studied including; A) conventional concrete rigid frame structure constructed in a staging area and lifted using self-propelled modular transporters (SPMTs) and transported to site, B) segmentally precast rigid frame structure, C) combi-wall system with integral steel superstructure, and D) secant wall with precast deck/T-beam superstructure.

The analysis highlighted that Alternative A: Conventional Concrete Rigid Frame emerged as the preferred option due to its lower cost, simpler construction process, proven durability, and minimized risk compared to Alternatives C and D. Although Alternative A required a three-day closure for construction, its method was well-established from a Highway 401 pilot project at Cornwall, Ontario (Choi & Small, 2016). Factors such as design complexity, vertical clearance, drainage, shoring, and future improvement potential also favored Alternative A. Conversely, Alternatives C and D presented challenges like more complex designs, additional shoring, special drainage requirements, more frequent traffic interruptions, and higher costs—making them less practical despite shorter full closure durations. Ultimately, Alternative A proved to be the most economical and feasible choice.

Figure 1: Structures Prior to Replacement

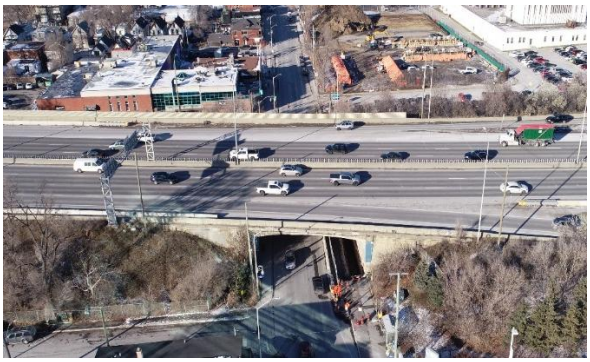
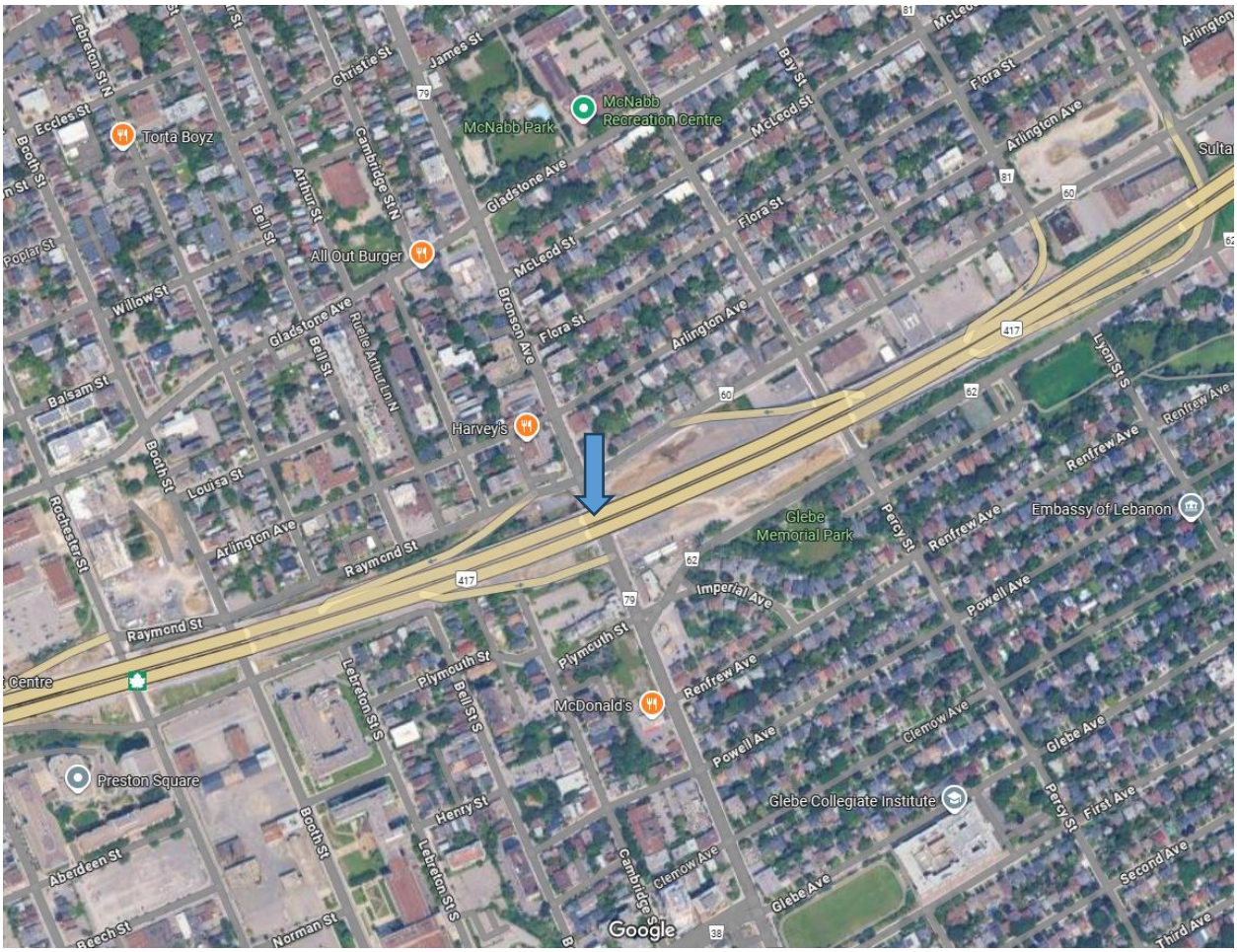


Figure 2: Site Map



Main Construction Challenges

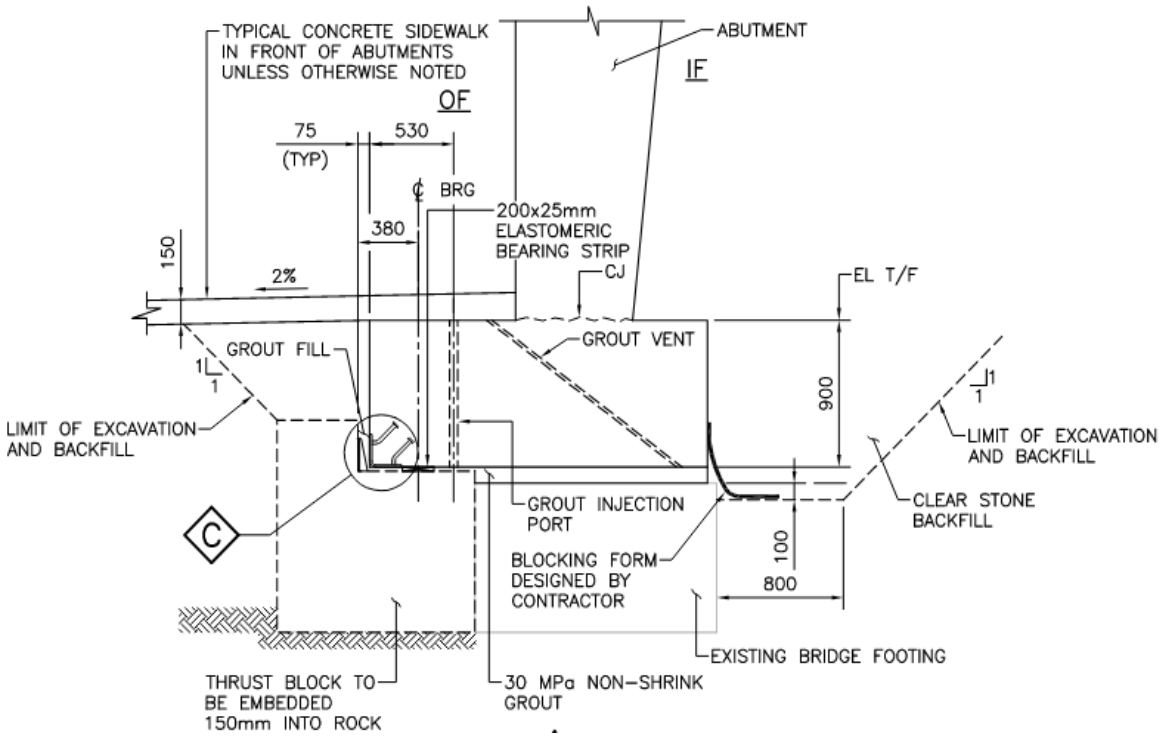
Reusing the Existing Footings

Removal of the existing footings would require more excavation and backfill compared to keeping the existing footings, in addition to demolition and removal of the existing footings. Furthermore, additional time during the weekend construction would be required to construct a concrete levelling pad to support the new footings. For these reasons, it was recommended that the existing footings remain, and the new footings be supported by the existing footings. The challenges associated with this are the fact that the conditions of the existing footings were unknow, and there was a possibility of damaging them during the removal of the existing structure.

To mitigate these challenges, a thrust block was constructed in front of the existing footings with the bearing seat being constructed approximately 100 mm above the existing footing. During the weekend closure, the toes of the new footings were placed on the bearing seat of the thrust block. The structure was supported by this footing configuration while the SMPTs are removed, and non-shrink grout was pumped through a concrete port in the new footing. The grout is used to fill the void between the new and existing footing, creating uniform support for the new footing once set.

The trust block is designed to resist the horizontal 'kicking' force that results from backfilling the structure, which eliminated the need to install dowels connecting the new footing with the existing footing, thus reducing the amount of work required during the RBR weekend.

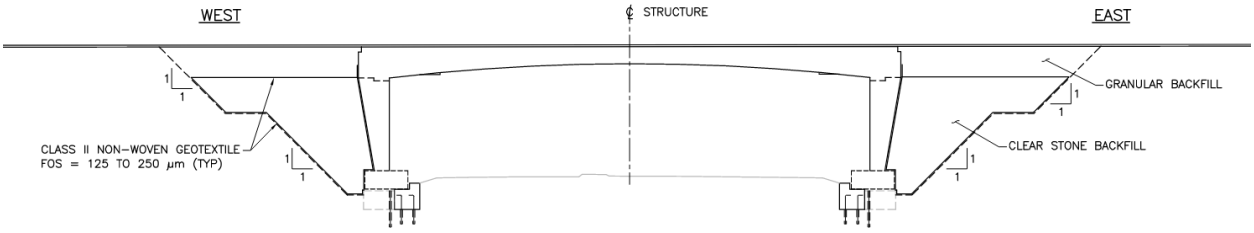
Figure 3: Thrust Block detail



Excavation and Backfilling Time

Due to the large quantities of excavation and backfilling required for the project, and the limited time available for Rapid Bridge Replacement (RBR)—only 82 hours—a time-efficient solution is necessary. To address this constraint, clear stone was used as the backfill material. Unlike traditional granular backfill, clear stone does not require extensive compaction, which significantly reduced the time needed for backfilling operations.

Figure 4: Excavations and Backfilling limits



RBR Movement and Construction Staging

Construction Staging

For the RBR process for the Rigid frames, the work Sequence was designed to take place per the following phases:

- Phase I: Preparation of temporary staging area and prefabrication of new structures;
- Phase II: Construction of thrust blocks and preparation works on the city streets;
- Phase III: Night work on Highway 417;
- Phase IV: Erection of the bridge within a full 82-hour weekend closure on Highway 417, and total city street closure of 3 weeks including RBR;
- Phase V: Completion of work on city streets;
- Phase VI: Construction of retaining walls on Highway 417; and
- Phase VII: Construction of approach slabs and median barrier walls on Highway 417 performed on weekends with lane restrictions.

Prior to the Rapid Bridge Replacement (RBR) operation, significant preparation needed to take place. The staging areas for the prefabrication of the structures at Bronson Avenue was the property on the south side of Highway 417 and on the east side of Bronson Avenue as shown in (Figure 5) .

Comprehensive surveys of the existing structures were conducted to confirm the locations and elevations of key elements, such as footings, and ensure alignment with the new prefabricated structures. Temporary support structures, including foundations, were designed and constructed to facilitate the prefabrication and transportation of the eastbound and westbound lane rigid frames. These prefabricated frames were equipped with attached wingwalls, barrier walls, waterproofing, and protection boards, with adjustments made to match the remaining parts of the existing structures and Highway 417 grades.

Following the completion of the RBR, additional work focused on finalizing construction and restoring areas affected by the process. Gaps between the new and existing footings were pressure grouted, and curbs, gutters, sidewalks, and asphalt were reconstructed. Electrical systems and pavement markings were installed to restore functionality and aesthetics. On Highway 417, Temporary pavement was replaced, permanent markings were applied, and all traffic lanes were reopened, marking the successful completion of the operation and the restoration of full traffic flow.

The challenges faced for the RBR method of the rigid frame structures at the initial stage of the design included lifting the heavy full structures, complete with footings, and lowering them into place at their final destination. The weights of the structures are shown in Table 1 below. These weights are about 28% higher than the heaviest lift reported in Ontario to date (Choi & Small, 2016).

Table 1. Weights of lifted structures

Structure	Approximate Weight
Bronson EBL	1773 tonnes
Bronson WBL	1780 tonnes

A very tight tolerance was specified for the construction of each component of the rigid frames to avoid any possible "fit" issues when placing the structures on top of the thrust blocks. Table 2 and Table 3 shows the main tolerances applied to the construction.

Table 2. Tolerances for the construction of the rigid frame footings

Dimension	Tolerance
Thickness	± 10mm
Length	±13mm
Width	±10mm
Sweep (curvature along length)	±10mm maximum ± 3mm over any 3m interval
Tilt along width	± 1.5mm
Tilt along length	±3mm
Twist along length	±3mm
Camber along length at underside of footing	±3mm maximum ± 1.5mm over any 3m interval
Perpendicular distance between footings	±10mm
Diagonal distance between west and east footing corners	±10mm

Table 3. Tolerances for the construction of rigid frames concrete walls

Dimension	Tolerance
Height of wall	+ 6mm
Total thickness of wall	±6mm
Sweep (curvature along length)	±10mm maximum ± 3mm over any 3m interval
Distance between walls at footing	± 6mm
Distance between walls at haunch	±13mm
Plumb over height of walls	±6mm

RBR Movement Plans

The new bridge sections were constructed near the highway at the designated staging areas (Figure 5) and then lifted using the JS500 jacking system mounted on SPMT's. The transportation and accurate placement of the bridge sections were carried out by Mammoet, while Kiewit-Dufferin ensured precise surveying and geometric monitoring during the process. String lines were used to detect and document any deflections, and where necessary, plywood shims were installed to correct deviations.

The final set-down of the bridge sections was accomplished with a tolerance of +/-10mm of the proposed alignment. Mammoet's self-propelled modular transporters (SPMT) facilitated precise adjustments thanks to their 360° maneuvering capability. Kiewit-Dufferin pre-marked set-down locations and conducted surveys to confirm the final positions of the bridges, ensuring compliance with the specified tolerances.

Before transportation, all necessary equipment, including the SPMT and JS500 jacking system, was assembled and verified in the staging area with a test lift. The SPMT was outfitted with crossbeams, secured, and aligned according to engineering drawings and as-built specifications. Once the bridge sections were transferred onto the transporters, tie-down chains were tightened to secure the load. Hydraulic adjustments made by the SPMT further enhanced flexibility during transportation, accommodating any irregularities in road grade or elevation.

During the set-down phase, deflections were monitored and measured due to changes in reaction points. The three-point suspension system of the transporters ensured that the structure was being fully supported in the same plane at all times, resulting in no additional deflections (Figure 6).

Figure 5: Staging areas and travel paths

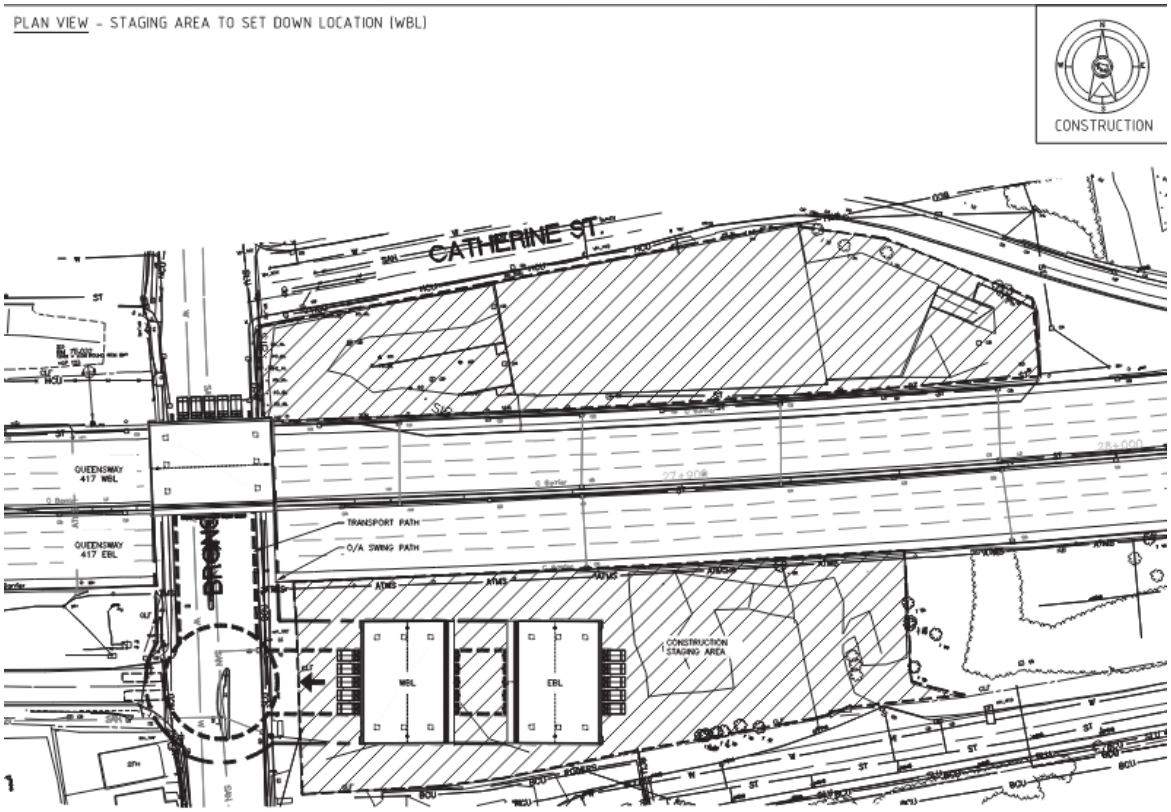
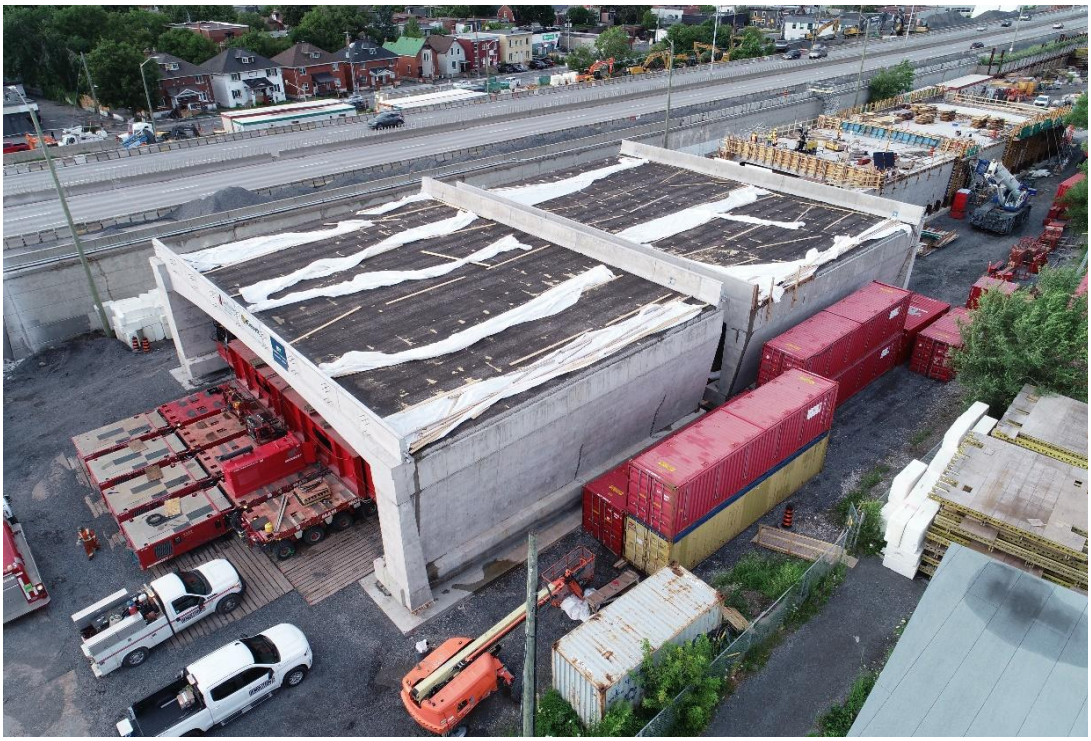
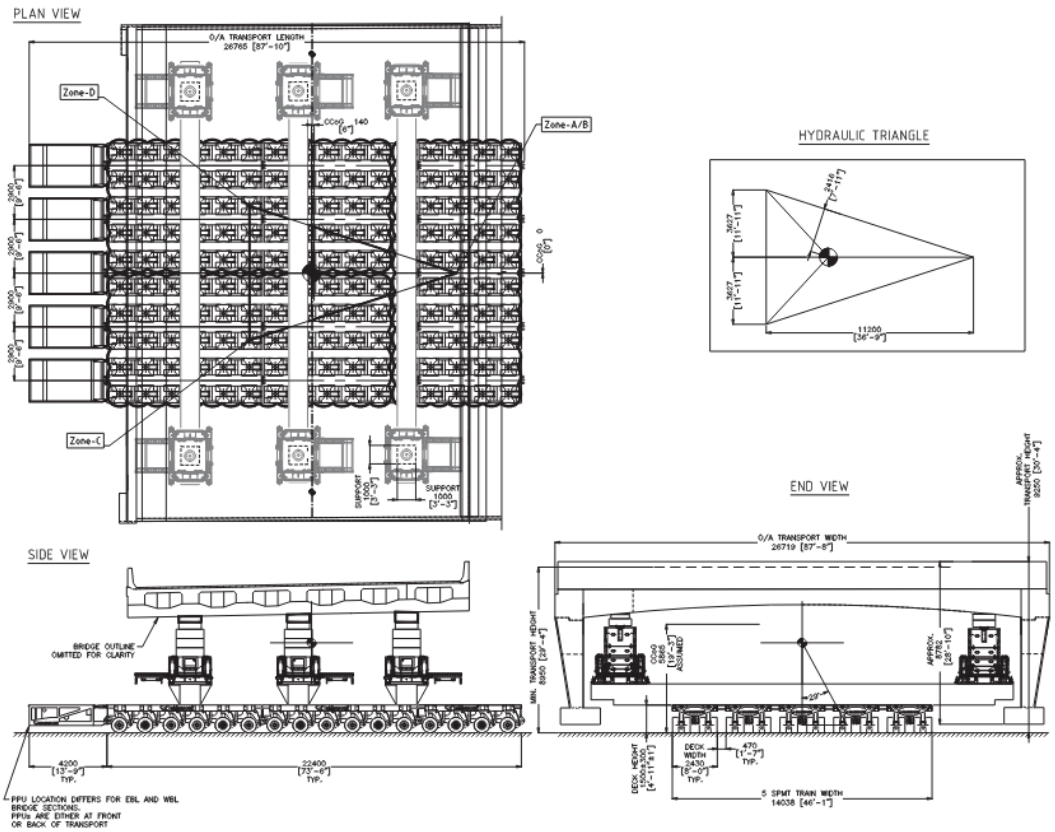


Figure 6: Lifting and Moving Structures





Construction Schedule:

The highway 417 detour was in effect at 20:00 on the 13th of July and the demolition started at 20:05. To aid both the excavation and demolition process, the approach slabs were sawcut before the RBR.

As the bridge abutment removal progressed towards the existing footings, a mini excavator paired with a hammer was employed for dental demolition around the footings. This process ensured that the top surface of both footings was flat and situated lower than the new thrust block before the bridge segments were positioned. After the demolition process was completed, rebar pieces sticking out of the existing footing needed to be cut using a blowtorch. The contractor had only one blowtorch available, which led to the biggest delay of the demolition operation (two-and-a-half-hours delay).

The SPMT equipment was used to transport both bridge structures from the staging area south of Highway 417 into their final locations. The first bridge structure supports the West Bound Lanes (WBL), and the second, East Bound Lanes (EBL). Five SPMT trains, each consisting of 18 axle lines linked together using six crossbeams, were used for moving Bronson bridge structures. Each structure was picked by six MJSs (three at each side).

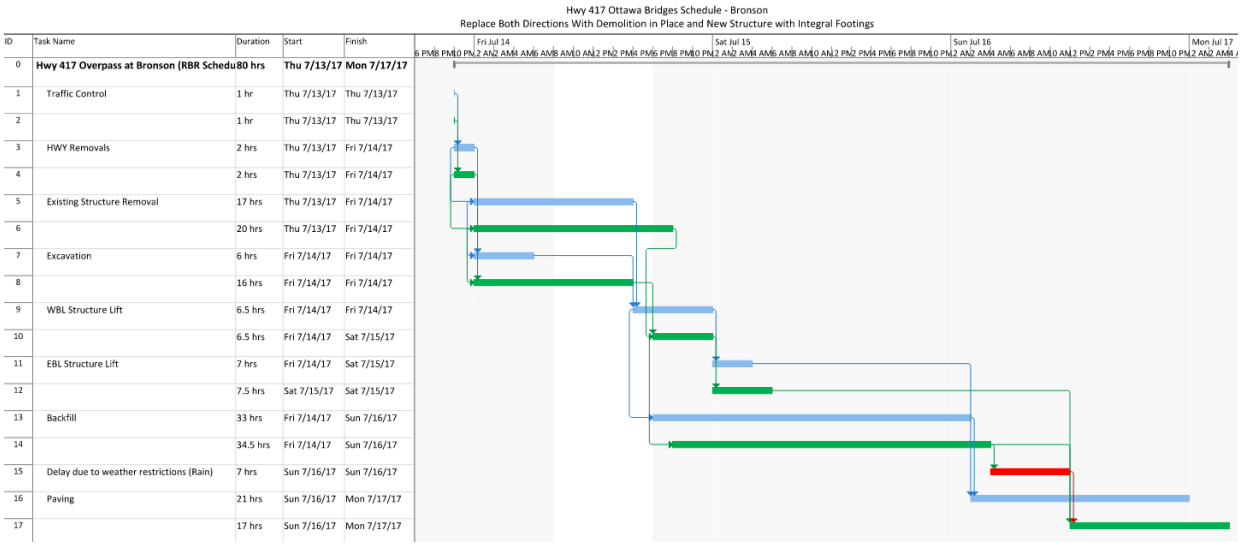
The WBL structure final movement started on Friday July 14th at 15:20 to its final location under 417 Highway using the assigned traveling path. When the structure reached Bronson Street, rotation started until the WBL was in line with Bronson Street. With final checks of structure position, the WBL structure was set down onto the thrust blocks. The SPMT equipment was returned to the staging area to transport the EBL structure. The rest of the EBL movement procedure was similar to the WBL, and it was completed on Saturday, July 15th at 04:58.

The geotextile installation started on Friday July 14th in the afternoon on both excavated slopes after the movement of the first bridge segment. The geotextile was fully covering the slopes before the EBL bridge segment moved. The WBL closure plates were installed shortly after the WBL was set in place and the EBL closure plates were installed shortly after the EBL was set in place. Later these gaps were closed with a CIP closure pour after the RBR weekend. The backfilling of clear stone behind the east and west abutments of Bridge 1 (WBL) began shortly after the bridge was set in place on Friday evening.

Paving was ready to start on Sunday, July 16th at 03:00. However, due to heavy rain, the paving was pushed to 9:00 to ensure that paving quality meets project standards. Paving lane marking and TCB install were fully complete at 03:55 on Monday, July 17th without the need to extend the weekend shutdown window.

All work was completed, and equipment moved from the highway by Monday at 04:00. The highway was reopened to the public at 04:10, approximately two hours before the highway closure deadline.

Figure 7: Planned Vs Actual Construction Activities schedule during RBR Weekend



ID	Task Name	Duration	Start	Finish
0	**Hwy 417 Overpass at Bronson (RBR Schedu**	**80 hrs**	**Thu 7/13/17**	**Mon 7/17/17**
1	Traffic Control	1 hr	Thu 7/13/17	Thu 7/13/17
2		1 hr	Thu 7/13/17	Thu 7/13/17
3	HWY Removals	2 hrs	Thu 7/13/17	Fri 7/14/17
4		2 hrs	Thu 7/13/17	Fri 7/14/17
5	Existing Structure Removal	17 hrs	Thu 7/13/17	Fri 7/14/17
6		20 hrs	Thu 7/13/17	Fri 7/14/17
7	Excavation	6 hrs	Fri 7/14/17	Fri 7/14/17
8		16 hrs	Fri 7/14/17	Fri 7/14/17
9	WBL Structure Lift	6.5 hrs	Fri 7/14/17	Fri 7/14/17
10		6.5 hrs	Fri 7/14/17	Sat 7/15/17
11	EBL Structure Lift	7 hrs	Fri 7/14/17	Sat 7/15/17
12		7.5 hrs	Sat 7/15/17	Sat 7/15/17
13	Backfill	33 hrs	Fri 7/14/17	Sun 7/16/17
14		34.5 hrs	Fri 7/14/17	Sun 7/16/17
15	Delay due to weather restrictions (Rain)	7 hrs	Sun 7/16/17	Sun 7/16/17
16	Paving	21 hrs	Sun 7/16/17	Mon 7/17/17
17		17 hrs	Sun 7/16/17	Mon 7/17/17

Structural Analysis

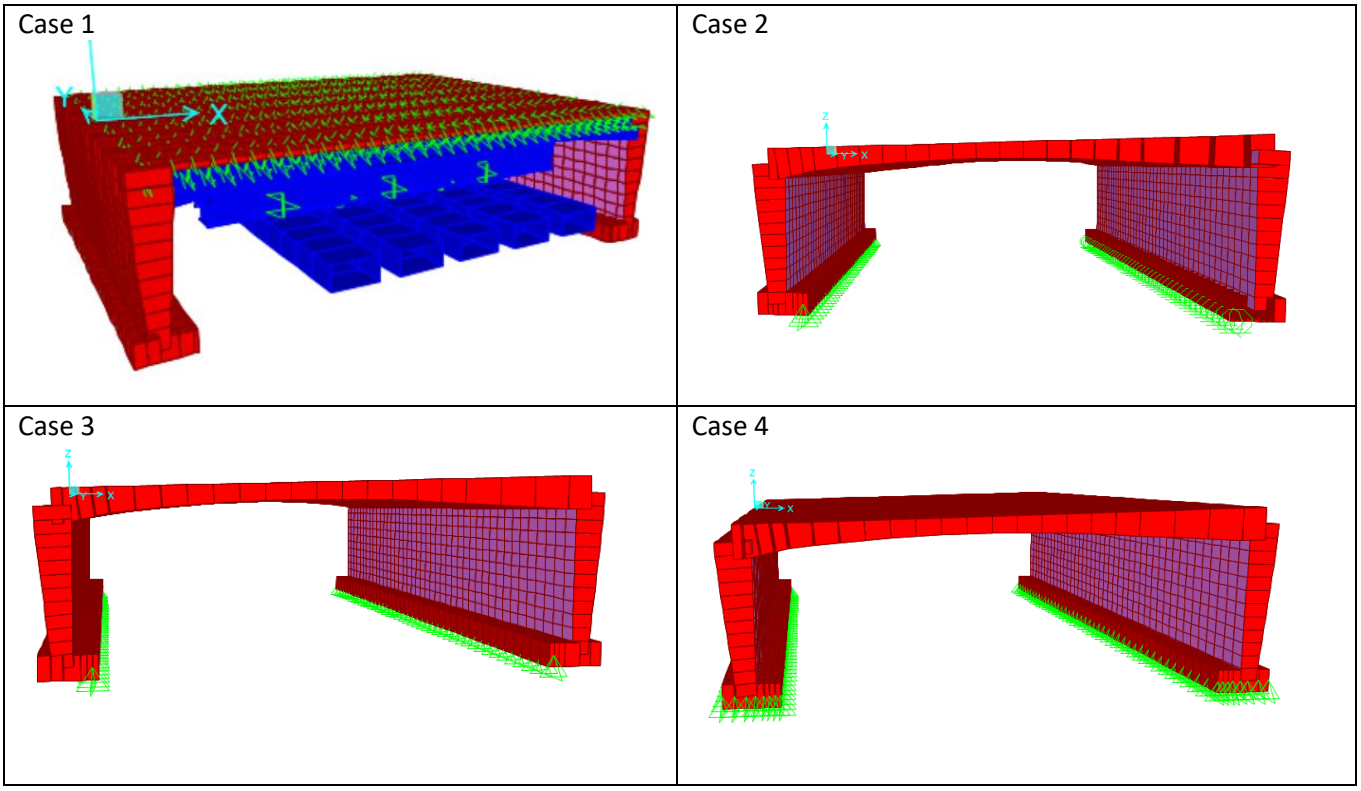
A comprehensive three-dimensional, linear elastic finite element (FE) analysis was carried out using the SAP2000 software to evaluate the structural design. The analysis employed four-node quadrilateral shell elements for the footings, concrete walls, and deck slabs. Four cases were considered during the analysis (Figure 8):

- ***Case 1: Structures supported on Self-Propelled Modular Transporters (SPMTs):***
  This case evaluated the temporary stresses when lifted at discrete points at the soffit near the haunch.
- ***Case 2: Structures supported on hinge–roller supports at the bearing location on the thrust blocks:***
  This case examined the structures immediately after being put down under the own weight load case only.
- ***Case 3: Structures supported on hinge–hinge supports at the bearing location on the thrust blocks*:**
  This case assumed full loads including on toe of new footing, including all dead, live, and earth pressures. This was carried out to account for any lack of full contact between the footing and the grout.
- ***Case 4: Structures in their fully backfilled, final state:***
  Assumed full contact between the footing and the grout.

A static analysis was performed, incorporating dynamic load factors following NCHRP recommendations to account for the moving loads on the structures when transported using the SPMT:

- Vertical direction: Dynamic load factor of 1.15 times the weight.
- Horizontal direction: Dynamic load factor of 1.05 times the weight.

Figure 8: Structural analysis cases



The analysis during the lifting of the structures showed that the rigid frame legs experienced a deflection of about 22mm inwards when lifted with the SPMTs Figure 9. It also showed that the deck experienced excess stresses at the pick-up locations which required the addition of 1000x1000mm jacking plinth reinforced with 5-16M Chromium rebars at both directions, with a 650x650x20mm elastomeric bearing placed prior to lifting the structures.

Figure 9: Rigid frame legs deflections during lifting

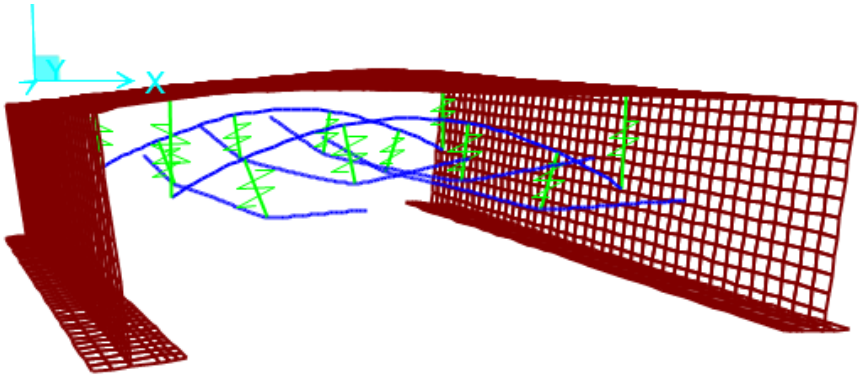
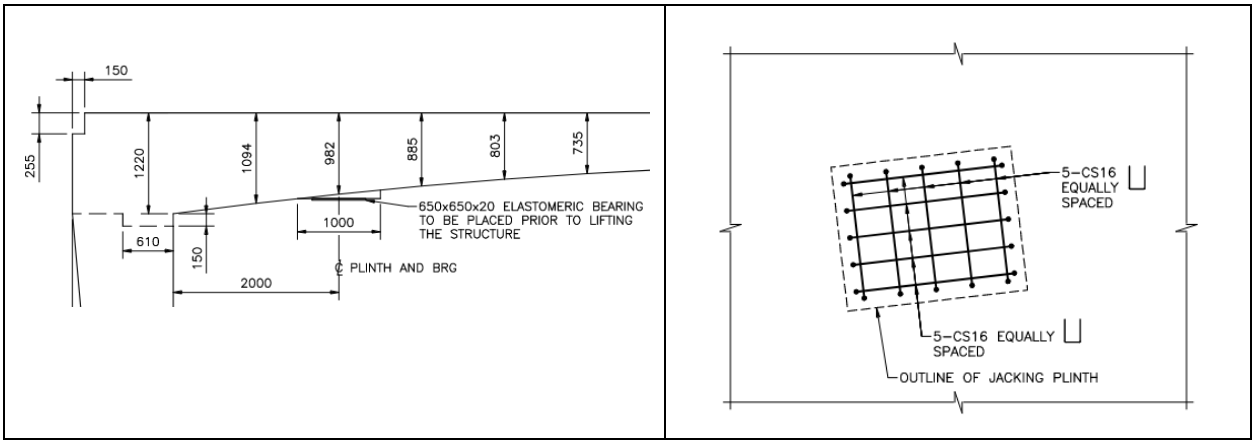


Figure 10: Jacking plinth details



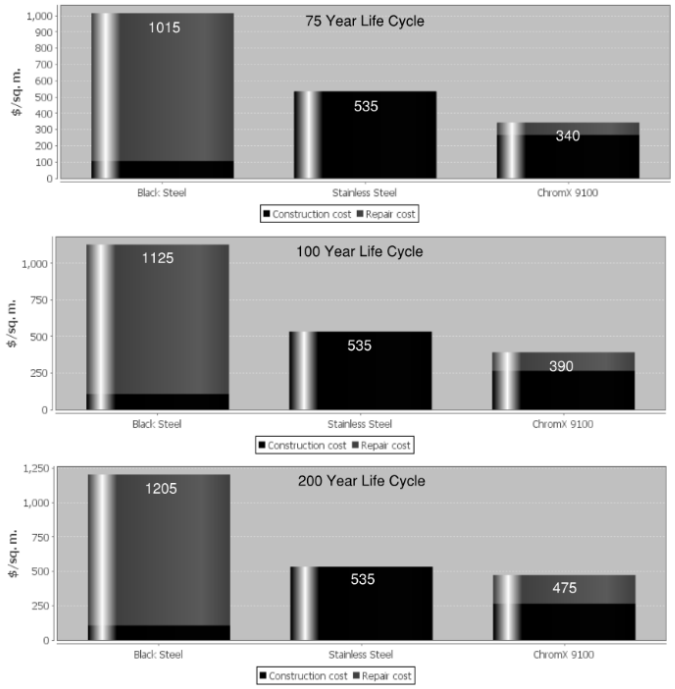
Premium reinforcement for deck soffit

Three types of reinforcing steel were considered for the reinforcement of the rigid frame structures; Black Steel, ChromX 9100, Stainless Steel. ChromX 9100 refers to a high-strength, corrosion-resistant reinforcing steel bar from the ChromX 9000 Series, developed by MMFx Technologies. Its standout characteristic is its enhanced durability, achieved through advanced micro-composite alloying that allows for superior performance in highly corrosive environments.

An analysis comparing the three types of reinforcing steel based on their life cycle cost, corrosion resistance, and durability for use in soffits of rigid frame structures was performed. It showed that Black Steel, which costs $3/kg, has the shortest corrosion threshold of 0.05% chloride content and a propagation time of 6 years, leading to frequent repairs and higher long-term costs. Stainless Steel, priced at $15/kg, offers significantly better corrosion resistance with a threshold of 0.50% chloride content and a propagation time of 50 years, but its high initial cost limits its cost-effectiveness. ChromX 9100 strikes a balance with a cost of $7.5/kg, a moderate corrosion threshold of 0.20%, and a propagation time of 17.5 years, making it a viable middle-ground option.

A life cycle cost analysis conducted using Life 365 software demonstrated ChromX 9100's cost-effectiveness over 75, 100, and 200 years as shown in Figure 11. Although its upfront construction costs exceeded those of Black Steel by $105,600 to $124,800 per structure, ChromX achieved a 67% reduction in life cycle costs compared to Black Steel and a 36% reduction compared to Stainless Steel over a 75-year period. This cost reduction stemmed from ChromX's increased durability, which minimized the frequency and cost of repairs. The analysis assumed fixed repair schedules, inflation at 2%, and a discount rate of 5%.

Figure 11: Construction and repair costs for steel alternatives



Sensitivity analysis further confirmed ChromX 9100 as the most cost-effective option across various parameters, including inflation rates, repair costs, and surface chloride content. While construction costs increased slightly—by 0.8% for structural work and 0.5% for the total project—using ChromX ultimately reduced the overall life cycle cost of the structures. Thus, it was recommended that ChromX 9100 to be used as a reinforcing material for soffits, combining durability with financial feasibility over the long term.

Conclusions

The successful completion of the Highway 417 overpass replacements at Bronson has demonstrated the effectiveness of the chosen strategies:

- **RBR methodology:** The selection and implementation of Rapid Bridge Replacement (RBR) with rigid concrete frames proved successful in minimizing disruption and ensuring efficient construction.
- **Construction Staging:** The detailed seven-phase RBR process, including off-site prefabrication and precise on-site execution using SPMTs, was a viable approach for this complex project.
- **Thrust Block Connection Successful:** The thrust block alternative for footing connections streamlined construction, mitigated risks associated with existing footings, and managed structural deflections effectively.
- **Structural Analysis:** The structural analysis should account for the various loading cases for the rigid frames installed using RBR method.

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