RAPID BRIDGE REPLACEMENT OF CONCRETE RIGID FRAME BRIDGES UTILIZING HEAVY-LIFT CONSTRUCTION TECHNIQUE

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ABSTRACT

A rapid bridge replacement (RBR) method was designed and used for the replacement of the Highway 401 twin overpasses at Cornwall Centre Road in Cornwall, Ontario. This RBR project was the first heavy-lift and move of large, approximately 1400 tonne, reinforced concrete rigid frame bridges in Ontario. The new structures were prefabricated in staging areas near the sites and moved to their final locations by specialized heavy-lift construction equipment, comprising self-propelled modular transporters (SPMTs). For the westbound lane structure, a segmental approach where a top rigid frame component and two bottom footing components were constructed separately and connected at their final location was adopted to reduce the weight of the structure due to limited space available for SPMTs. For the eastbound lane structure, the entire rigid frame integrated with footings was constructed and transported by specially configured SPMTs and lifting system that included climbing jacks to lower the entire structure 1.5 m to its final position after transportation. A three-dimensional, linear elastic finite element analysis was utilized for design due to the high skew (51.5°) of the rigid frames to ensure the strength and stability of the structures during lifting and transportation, and their final backfilled service condition. The cost for RBR construction was approximately 25% higher than that of the conventional construction. However, the project confirmed that it is feasible to use the RBR method of construction for complex rigid frame bridges to significantly reduce the duration of traffic impacts for the construction of these types of structures.

Keywords: Rapid bridge replacement (RBR), Self-propelled modular transporters (SPMTs), Concrete rigid frame, segmental, staging area, climbing jack

1. INTRODUCTION

1.1 Background of Structures and Project

The Highway 401 Overpass at Cornwall Centre Road, Cornwall, Ontario was originally constructed in 1962. The overpass comprised twin structures for the eastbound and westbound lanes separated by conventional reinforced concrete retaining walls in the median. Each structure was a single span bridge with reinforced concrete deck slab over steel girders supported on conventional reinforced concrete abutments that accommodated two lanes of traffic. Figure 1 shows the elevations of the structures prior to the replacement, viewed from Cornwall Centre Road.

The structures were first rehabilitated in 1994 and the work included concrete deck overlay, new barrier walls, waterproofing, and paving. The second structure rehabilitation comprising structural steel recoating was completed in 1997. In 2009, due to concerns related to leaning and continuing movement of the west median retaining wall, the Ministry of Transportation in Ontario (MTO) installed a deadman and tie backs to restrain the wall and instituted a program to monitor the walls movement. In addition, MTO authorized Genivar Inc. (now WSP) to perform a rehabilitation/replacement study of the existing structures.
The preliminary design study recommended that the existing structures be replaced with concrete rigid frame structures. In 2011, the MTO retained MMM Group (a member of WSP) to perform the detailed design for the replacement of the twin overpass structures.

As part of the detailed design assignment, MTO requested that the rapid bridge replacement (RBR) method of construction be investigated for the replacement of the rigid frame structures. In general, the RBR construction method included pre-constructing the structure at a staging area close to the site, which was then transported to its final location utilizing self-propelled modular transporters (SPMT’s) after the existing structure was removed. Other RBR projects in Ontario have been successfully completed for conventional girder bridges and for the superstructure replacement only (Cerullo et al. 2015). RBR construction for a concrete rigid frame structure had not been attempted before in Ontario, but had successfully been performed in France (SARENS 2008).

The new WBL and EBL structures are single span concrete rigid frame structures carrying two 3.75 m lanes of Highway 401 with a left shoulder of 2.5m and a right shoulder of 3.0m. The span length of structures is 11.8m with a constant skew of 51.5°. The depth of the rigid frame deck slab is 500mm at mid-span and 1000mm at the legs. The wall sections varied in thickness from 1000mm at the top to 800mm at the top of footings. The footings were 2.4m wide and 800mm thick. Figure 2 shows the elevation and plan of the new structure.

After in-depth investigation of RBR alternatives, a segmental RBR method where a top rigid frame component and two bottom footing components were separately constructed, transported, and connected at their final locations was adopted by MTO Executive in July 2011. Separate components were required to reduce the weight of the structure, due to limited space available for the SPMT’s considering the excavations and lowering of the structure required to
accommodate frost depth. A Constructability Review was carried out on June 20th and 21st, 2012. During the review concerns were expressed with regard to “fit” issues at closure joints between the footing components and rigid frame component. Work done during and subsequent to the Constructability Review confirmed that it is possible to transport the entire rigid frame with footings in a single piece. Accordingly, the EBL replacement structure was re-designed as a rigid frame with integral footings. The WBL replacement structure with segmental approach was maintained as a pilot construction project to simulate conditions where a rigid frame could be connected to existing pile caps/footings.

AECOM was awarded the construction contract and construction was completed in September 2015. The cost for RBR construction was approximately 25% higher than that of the conventional construction. However, the success of the project proved that the RBR construction of large rigid frame bridges are feasible, and can significantly reduce the duration of traffic impacts for construction of these types of bridges.

1.2 Rapid Bridge Replacement (RBR) Construction

RBR construction included prefabricating the concrete rigid frame structures in staging areas, and moving them to their final location with self-propelled modular transporters (SPMTs). A typical six-axle SPMT has a capacity of 204 tonnes (34 tonnes per axe) while modern SPMTs can accommodate up to 60 tonnes per axle. Figure 3 shows a typical SPMT consisting of six synchronized axles.

![Figure 3: Typical six-axle SPMT (FHWA 2007)](image)

Loaded SPMTs typically travel at a walking pace of 4.8 km/h and can travel up to 11.2 km/h depending on load and the ground condition. The SPMT platform can be vertically adjusted up to 0.6m to keep the load horizontal without distortion while traversing uneven and sloping ground surfaces. SPMTs can travel on uneven terrain with surface variations up to 457 mm and on grades up to 8 percent, depending on ground surface friction. A steel base plate is often placed on the ground along the path to distribute the load over soft soils and prevent rutting. Detailed information on the SPMTs can be found elsewhere (FHWA 2007).

Equipment for vertical lifting can be mounted on the SPMT platform as needed. Equal loads are maintained on each axle line through the SPMT’s three-point or four-point hydraulic suspension system, which consists of two hydraulic rams per axle line with each ram attached to a hinged elbow supported by two wheels. If the ground settles during a bridge move, the hydraulic system compensates for the height difference.

A “Sliding” RBR method, where the pre-fabricated concrete rigid frame structures adjacent to the existing bridge are moved into position by “sliding” on pre-constructed temporary footings, was also investigated. However, this method was expected to require longer construction duration compared to the use of SPMT’s, so this alternative was not carried forward.

The staging areas selected were located as close as possible to the site, near the northeast and southeast quadrants for the WBL and EBL replacement structures respectively, to minimize the travel distance and the environmental impact. Figure 4 shows a plan view of the project site including staging areas for WBL and EBL structures.
2. FOUNDATION

Based on the results of the boreholes and the existing overpass foundation conditions and performance, shallow foundations were considered to be the preferred option for the replacement of the structures. For RBR construction, the existing foundation was re-used to found the new concrete rigid frame structures to reduce the depth of excavation, structure lowering required to accommodate frost-depth in the Cornwall area, and to eliminate the need to remove the existing footings. In addition, utilizing the existing footings in this manner significantly reduced the required size of the new rigid frame footings, thereby reducing the load of the structure. This also shortened the construction duration by eliminating excavation and removal of the existing footings from the work required.

The existing footings were prepared to receive the new footings by constructing a mass concrete leveling pad on top the old footings after removal of the existing abutment walls, to eliminate any large surface variations that may have existed. The new footings were placed on steel shim plates and thin elastomers to provide a gap between the underside of the new footings and leveling pad, which was later filled with cementitious grout. Dowel bars set in epoxy grout in cored holes were used to connect the new footings to the existing, to prevent sliding due to horizontal earth pressures from structure backfilling. Figure 5 shows the design details and a photograph during construction.
3. WBL RBR – SEGMENTAL APPROACH

The challenges faced for the RBR method of the rigid frame structure at the initial stage of the design included lifting the almost 1400 tonne structures, complete with footings, and lowering them 1.5 m into place at their final destination. The road on which the SPMTs were to travel is only a local road and fitting enough SPMTs under the structure to carry the load was problematic. In addition, the heavy weight of the loaded SPMTs caused high lateral earth pressures that pushed aside any object close to their path. The latter problem was resolved by reconstructing the road with low performance retained soil system (RSS) walls, comprising layers of geotextile and gravel, to permit vertical sided excavations.

A segmental RBR method consisting of a top rigid frame component and two inverted T-footing components was developed and investigated to reduce the weight due to limited space available for SPMTs. By separating the footings, the load was reduced to 1030 tonnes for the top piece which could be moved by two rows of SPMTs. Separating the footings also solved the lowering problem because the 185 tonne footings could now be picked up and lowered with strand jacks. Figures 6 and 7 show the RBR configurations at the staging area and the final location with the RSS wall constructed along the Cornwall Centre Road for lifting and transportation of two bottom footing components and a top rigid frame component, respectively.

![Figure 6: WBL RBR Construction – Footing Move (Stage A)](image)

![Figure 7: WBL RBR Construction – Rigid Frame Move (Stage B)](image)

The vertical faces of RSS wall constructed adjacent to the excavation to control the lateral earth pressures had an additional benefit of increasing the available travel width, which could accommodate up to three side-by-side SPMTs. This additional space was exploited by the Contractor to allow the use of more SPMTs than originally anticipated during the design stage. The heavy-lift subcontractor Mammoet opted to use three trains of three SPMTs for a total of nine SPMTs for the EBL move where the heavier weight from the single piece rigid frame integrated with the footings needs to be lifted and transported. The same SPMT configuration was applied to the WBL move for convenience.
Erection started with the bottom footing components which were transported and placed at their final location with a horizontal offset of 25mm relative to the span. This off-set was necessary to accommodate the outward deflection of the legs of the top rigid frame piece when it was lifted. Next, the top rigid frame component was transported by the SPMTs and placed on the footings, and then the closure joint was constructed. Figure 8 shows the lift and transportation of top and bottom components.

![Figure 8: WBL RBR Construction – Left: Footing Components, Right: Rigid Frame Component](image)

Having three components instead of one for the new structure required 24m long horizontal keyed construction joints in the walls and tight construction tolerances. Furthermore, the tolerances and footing component placement also had to take into account the deflection of the legs of the rigid frame when lifted. A very tight tolerance was specified for the construction of each component to avoid any possible “fit” issues. Reinforcing steel bars were also placed with tight tolerances to avoid conflicts between the upper and lower headed bars in the construction joint. In addition, prior to and during lifting and transportation, the top and bottom components were carefully monitored and precisely located to ensure a proper fit between components. Table 1 shows the main tolerances applied to the construction.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Tolerance</th>
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</thead>
<tbody>
<tr>
<td>Width of key at top of wall of WBL footing component</td>
<td>+/- 3mm</td>
</tr>
<tr>
<td>Width of key (stem) at bottom of wall of WBL rigid frame component</td>
<td>+/- 3mm</td>
</tr>
<tr>
<td>Depth of key at construction joints</td>
<td>+/- 6mm</td>
</tr>
<tr>
<td>Length of key at bottom of key (wall of rigid frame component) and top of key (wall of footing component)</td>
<td>+/- 13mm</td>
</tr>
<tr>
<td>Insert or headed bar location along length of wall</td>
<td>+/- 13mm</td>
</tr>
<tr>
<td>Insert or headed bar location along width of wall</td>
<td>+/- 10mm</td>
</tr>
<tr>
<td>Distance between walls at key</td>
<td>+/- 6mm</td>
</tr>
<tr>
<td>Distance between walls at haunch</td>
<td>+/- 13mm</td>
</tr>
<tr>
<td>Plumb over height of walls of rigid frame component</td>
<td>+/- 6mm</td>
</tr>
</tbody>
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Figure 9 shows the closure joint details between top rigid frame component and the bottom footing components. 50mm clearance was provided at both sides of the key to receive the top rigid frame component. Headed bars projecting from the top and bottom components were utilized to reduce the lap splice length for the heavy bars passing through the construction joint. The headed bars projecting from the footings were connected to mechanical connectors after the rigid frame was placed to avoid the interference of the bars heads while the rigid frame was lowered. The shear key groove on top of the wall section of the inverted T-footing was partially filled with cementitious gout immediately before the top rigid frame component was placed, so that any possible gap (void) between bottom and top components will be filled with grout before grout sets. After the top rigid frame was placed, the headed bars were installed and the closure joint was constructed with normal concrete by form and pump method.
After the completion of the remaining works for WBL structure including: construction of a portion of the median RSS wall; backfilling; approach slab construction; waterproofing; and pavement, the EBL traffic was shifted to new WBL structure for the EBL structure replacement.

4. EBL RBR – SINGLE PIECE MOVE

For the EBL structure, the total weight of the rigid frame structure including footings is approximately 1400 tonnes. Originally, two trains of four modern SPMTs with of 48 tonnes per axle were considered to transport the structure. However, as described in the preceding section, the Contractor utilized the extra width provided from the use of RSS wall and applied three side-by-side SPMTs with a capacity of 34 tonnes per axle for a total of nine SPMTs for the EBL move. For this configuration, the Contractor introduced the tie rods anchored to and between the legs of the rigid frame during lifting and transportation to control the distortion of the structure due to the high skew. It should be noted, however, that the distortion issue could also be resolved by using a different configuration of the SPMTs and lifting framing system. Figure 10 shows the RBR configurations for the EBL move with two trains of four SPMTs.

Climbing jacks between the lifting frame and SPMTs were used to lower the structure to its final position because the lowering distance was beyond the SPMTs stroke limit. Each jacking cylinder is connected, via hydraulic hoses, to a constant displacement jacking pump which can be either diesel or electrically driven. The pump discharges the same volume of oil to each jacking cylinder, irrespective of load, which ensures that each jacking cylinder extends at the same speed, regardless of pressure. Therefore, the structure will be lifted (or lowered if jacking down) simultaneously by all the jacking cylinders as the stroke of each cylinder is equal at any time. This climbing jack system was secured with bracings. Figure 11 shows the EBL move with three side-by-side SPMTs and the climbing jack used in the EBL move.
5. STRUCTURAL ANALYSIS

Due to the high 51.5° skew, a three-dimensional, linear elastic finite element (FE) analysis was performed for the design using MIDAS (2011) and checked with SAP2000 (2014). Both MIDAS and SAP2000 are well known commercially available FE analysis software. Four-node quadrilateral shell elements were used to model the concrete wall, footings, and deck slab. The analysis considered two phases including: 1) structures on SPMTs; and 2) structures in their final backfilled condition. The structure on SPMTs was analyzed to check the strength and stability of the structure during lifting and transportation and to investigate the effect of the discrete lifting points in the walls. Figure 12 shows the modeling of the concrete structures for lifting and transportation.

The lifting analysis design assumed infinite stiffness for the lifting frame and SPMTs, which provided zero vertical differential displacement between the block-outs when the structure was lifted. During construction, the Contractor analyzed the structure in the lifted condition with the actual stiffness of the SPMTs, SPMT locations, and the lifting frame designed by the Contractor, to independently check the strength, stability, and stresses imposed on the structure during the move. As described in the preceding section the Contractor introduced additional bracing consisting of tie rods installed between the legs of the rigid frame to limit the twisting of the structure resulting from the flexibility and configuration of the SPMTs and lifting beams.

The lifting points comprised block-outs in walls of the rigid frames, into which steel beams were inserted to lift the rigid frame components. Three (3) block-outs were provided on each wall for the WBL structure while four (4) block-outs on each wall were required for the EBL structure to lift the heavier structure. The size of the block-outs was determined to suit the steel beam and elastomeric bearings on top of the steel beam were designed to achieve the uniform pressure to the concrete and account for the deflection of the lifting beams. Due to the high skew of the structure, the reactions at the supporting points near obtuse corners were higher than those near the acute corners. As such, bigger elastomeric bearings were designed at the block-outs near the obtuse corners. Additional reinforcing bars were placed around the block-outs based on the strut-and-tie analysis to prevent any excessive cracks during
lifting. The Contractor overlooked the installation of the elastomeric bearings during lifting and transportation resulting in some cracks and spalling of the concrete cover around the block-outs, which were later repaired.

After the rigid frames were placed, the reinforcing steel bars connected to mechanical connectors were installed in temporary block-outs which were then filled with concrete by form and pump method. Figure 13 shows design details at block-outs and cracks found during placement.

The structures in their backfilled condition were analyzed and evaluated in accordance with the Canadian Highway Bridge Code (CHBDC), CAN/CSA S6 (2006). It was found that the moment and shear forces at the obtuse corners were higher than those at the acute corners because of the high skew. Additional reinforcement comprising a third layer of reinforcing placed perpendicular to the walls was required for the obtuse corners to meet the strength and serviceability requirements in these highly stressed locations. Figure 14 shows stress concentration at the obtuse corners and the reinforcing details at these locations.

The maximum rotation at the obtuse corners at the top of the deck toward the Cornwall Centre Road due to unbalanced earth pressure caused by high skew was checked and confirmed that the magnitude of the rotation was not significant due to the high stiffness of the wall. Dowel bars to connect the new and existing footings were designed to resist the unbalanced earth pressure and no sliding and rotation of the existing footings on the existing founding material was confirmed.
6. COMPLETION OF THE PROJECT

Traffic analysis confirmed that the single lane operation on Highway 401 is feasible during RBR construction period with no queuing and acceptable speed reductions in the work zones during typical peak periods, and manageable queuing on long-weekends. AECOM undertook demolition of the structure in the spring of 2014 and completed installation of both structures by fall 2015. Currently, both lanes are fully operational and carrying normal Highway 401 traffic.

The construction bid price for this RBR project was 25% higher than the estimated cost for the conventional construction. However, the project confirmed that it is feasible to use the RBR method of construction for complex rigid frame bridges, to significantly reduce the duration of traffic impacts. The project also confirmed that temporary RSS (geotextile) retaining walls can be used to support heavy moving loads near the face of the walls.

ACKNOWLEDGEMENTS

Sincere thanks to the Ministry of Transportation for the opportunity to work on this challenging project. The completion of this complex project was made possible by the following teams.

- AECOM, General Contractor;
- Morrison Hershfield, Contract Administrator;
- Mammoet, RBR Operator;
- SARENS Group, RBR advisor; and
- Alston Associates, subconsultant for design of temporary RSS walls.

REFERENCES


