Evolution of Bridge Practices in Ontario, Canada

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Abstract

The Ontario Ministry of Transportation (MTO) manages provincial structures in Ontario including 2850 bridges. Following an extended period of fiscal restraint, the last decade has marked a dramatic increase in bridge construction work, with rehabilitation of a third of the provincial bridge inventory.

Bridge design and corrosion protection have evolved over the last 60 years. The practice of bridge rehabilitation is well-established in Ontario. Through the 1990s, standards were introduced for integral abutments, semi-integral abutments, and flexible links slabs between simply-supported spans to improve a bridge's durability in initial construction or rehabilitation. Accelerating bridge construction by reducing time on site is a current focus. The MTO has tried many forms of prefabrication.

Introduction

The Ministry of Transportation in Ontario (MTO) is responsible for managing the bridges on the provincial highways of Ontario. Assets include 2,850 bridges, 2,000 culverts, a handful of cut-and-cover tunnels (tunnels exceed 90 m in length), and over 2,000 sign support structures. The MTO maintains a set of standards and specifications for bridge construction, developed in collaboration with product suppliers and General Contractors (represented by the Ontario Road Builders Association), which are generally followed by municipalities and transit agencies for the 14,000 other bridges in Ontario.

The structural function of the MTO has evolved from over 300 staff in the 1970s, working on everything from bridge design and research to reviewing municipal bridge designs, to 110 staff today, focused primarily on managing consultants' work and construction issues. The MTO designs in-house around 10% of bridge work, either new or rehabilitation, to maintain expertise and attract, train, and retain staff. Legislation in Ontario requires that all bridges be inspected within every two calendar years, and MTO engineers inspect at least 50% of the provincial bridges in any calendar year to maintain first-hand knowledge of the structures.

Ontario covers a broad geography with highways covering latitude of 42° to 50° resulting in major differences in winter conditions and construction season. Reliable weather for bridge construction varies between 5 months in Northern Ontario to 8 months in southern Ontario. Overall, there are 1060 bridges across water, 286 over or carrying rail, and 1508 highway bridges. In Northern Ontario 74% of the bridges (603 of 819) span water.

Overview of Ontario's Provincial Bridges

Fig. 1 shows the age distribution of Ontario's provincial bridges. The 1960s was a time of major expansion of the highway network. Hwy 401 through Toronto, constructed in the 1950s as a four lane highway, was widened to a core/collector highway with 16 lanes in some locations. Bridges were completely demolished and rebuilt at four times the length, only 15 years after their initial construction. The expansion carried on until the 1980s. The 1990s saw the construction of Hwy 407, Ontario's first electronically tolled highway which was privatized in 1999 and is therefore not included in the bridge count. Since 2000, highway expansion slowed dramatically while bridge rehabilitation work increased significantly as the bridge inventory ages. From 2009 to 2014, the MTO tendered work on over 700 bridges, a quarter of the provincial inventory. Of these, 15% were new bridges as part of highway expansion, 13% were replacements, and the balance was rehabilitation (4% were widened during rehabilitation). In 2016, the average age of a bridge in Ontario was 39 years.

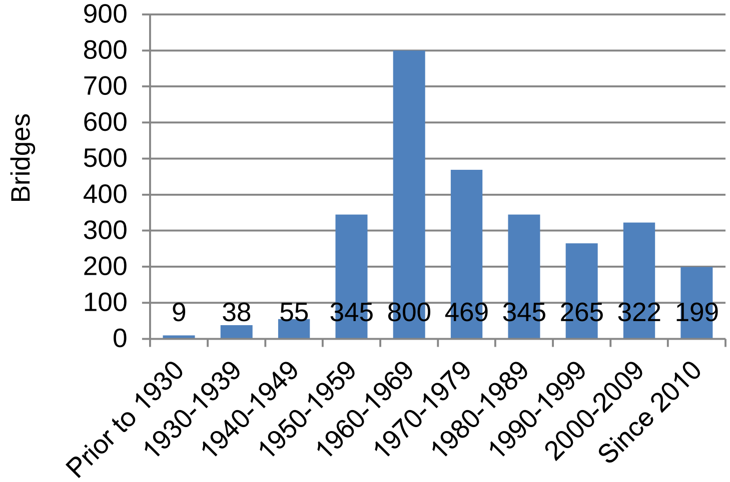

Fig. 1: Decade of construction of Ontario's provincial bridges (2016 data).

Several major changes in construction practice influence the way each bridge is managed. An historical understanding of corrosion protection practices in Ontario sets the stage for bridge rehabilitation needs. In 1962, a mechanical deck finishing machine was introduced in Ontario on the Garden City Skyway, eliminating the need for a bituminous wearing surface to provide a smooth driving surface. By 1965, the MTO was constructing exposed concrete decks on all bridges with typically 40 mm cover to reinforcement. By 1973, the MTO had observed delamination and spalling on bridge decks due to high chloride content from de-icing salt use and realised it was a mistake to have built exposed concrete bridge decks (Lai, 2008). From that point forward, all bridges were waterproofed and paved.

The MTO has a history of bridge rehabilitation dating back to the 1970s. Rehabilitations in the 1980s consisted of adding concrete overlays to exposed concrete decks, waterproofing and paving, and replacing open expansion joints with strip-seal expansion joints which contained water at the roadway surface. Bridges constructed in the 1950s or 1960s are now being rehabilitated for a second time. Meanwhile, the MTO is starting to rehabilitate many bridges constructed in the 1980s, which were designed with better durability practices and constructed with better materials and quality control.

MTO's bridge management practice for two decades since 1990 was driven by fiscal constraint and outsourcing of engineering services. Guidelines and strategies were geared to favour rehabilitation over replacement, with the objective of distributing funding to preserve the largest number of bridges and postpone larger expenditures. At the same time, preservation management and pro-active maintenance of structures in good condition were not the focus since they do not represent immediate needs based on the Bridge Condition Index (BCI), a quantitative measure which captures the remaining economic worth of a bridge calculated from actual inspection data. During the same period, the scope of rehabilitation has gradually expanded to embrace details of new construction practice. A typical rehabilitation includes barrier replacement, concrete refacing at piers or abutments, bearing replacement, and reconstruction of the deck ends. In many cases, the construction duration of rehabilitation approaches that required for replacement. For small bridges, the cost of rehabilitation can be considerable owing to fixed costs associated a number of operations. Fig. 2 compares the costs of bridges rehabilitated and replaced. Provincially, the unit cost ($ CDN per m² of deck area) for bridge rehabilitations is on average 27% of replacement, but regionally the median rehabilitation cost is closer to 35% of replacement. For bridges constructed after 1978, a lesser scope of rehabilitation (i.e. replacement of waterproofing and expansion joints) is adequate based on condition but some designers continue to apply a treatment similar to older bridges.

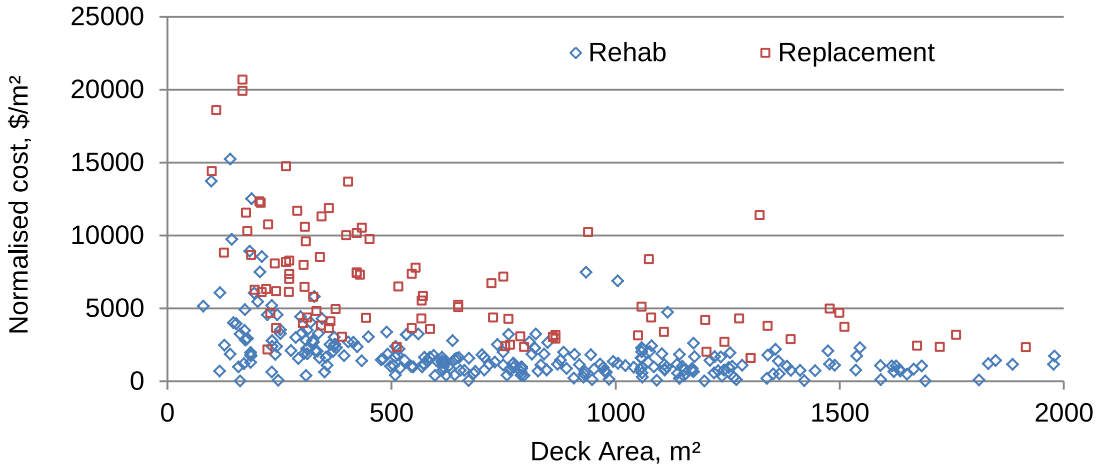

Fig. 2: Cost of bridge work tendered 2009 to 2014 (costs are average of lowest 3 bidders, for bridges with less than 2000 m²).

In 2014, the Ontario government, as well as the federal government, committed to investing in infrastructure. With increased investment, the objective of infrastructure management should be to maximize the rate of return on the investment. For structures which could undergo a major rehabilitation but border on need of replacement, the MTO considers replacement where there are clear benefits. Benefits include reduced risk of unknown conditions (associated with an existing structure), longer service life of the asset, less future traffic disruption, less total traffic disruption over a given life cycle, design for durability (e.g. integral abutment details, corrosion protection, and premium materials), potential geometric improvements to the roadway alignment, and the potential for functional improvements. The timing of replacement is based on operational needs and funding availability. Based on past experience, some types of rehabilitation will approach the cost of bridge replacement. For example, replacing a concrete deck on existing steel girders, followed by recoating the girders, will cost more than replacing the entire superstructure. A 2015 policy directs designers to select or consider replacement for projects where rehabilitation needs are substantial.

Corrosion Protection Policy

In response to observed deterioration of bridge concrete, in 1973 the cover to reinforcement was increased to 50 mm (from 25 or 40 mm), and bridge decks were waterproofed. In 1978, the MTO introduced a corrosion protection policy which sets standards for the use of waterproofing and premium materials to reduce long-term deterioration. Components exposed to de-icing salts and deck tops were detailed with a cover of 70 mm and epoxy-coated reinforcement. An end-result specification for waterproofing in 1996 improved waterproofing material quality and consistency of thickness. In 1999, stainless steel was added to the corrosion protection policy for highly exposed components such as concrete barrier walls, and high performance concrete was used on some bridges, although phased out in 2008 due to unsightly shrinkage cracking

(HPC is being reintroduced with updated specifications). In 2012, epoxy-coated reinforcement was discontinued and replaced with stainless steel or glass fibre reinforced polymer (GFRP) in components exposed to chlorides (Bridge Office, 2013).

MTO's current corrosion protection policy requires a cover of 70 mm to reinforcing steel at the top of the deck slab, waterproofing of the bridge deck with a hot-poured bituminous membrane of 5 mm nominal thickness overlaid with a protection board and paved with two lifts of asphalt for a total thickness of 90 mm, and premium materials for highly exposed elements of the bridge (e.g. pier columns within the splash zone, barriers, curbs, deck cantilever overhangs). Stainless steel has been used selectively since 1998. MTO accepts only 316LN and Duplex 2205 grades of stainless steel due to their superior resistance to pitting corrosion for components directly exposed to high chlorides. In future revisions, other grades of stainless steel such as Duplex 2304, may be incorporated into the corrosion protection policy for components that are not directly exposed to chlorides. GFRP was introduced in 2005. Both stainless steel and GFRP reinforcement are now commonly incorporated into routine bridge work, as shown in Fig. 3. Premium reinforcement is almost always used in traffic barriers. Fig. 4. shows the reinforcement in new concrete barriers (in new bridges and rehabilitations) for contracts tendered from 2009 to 2014.

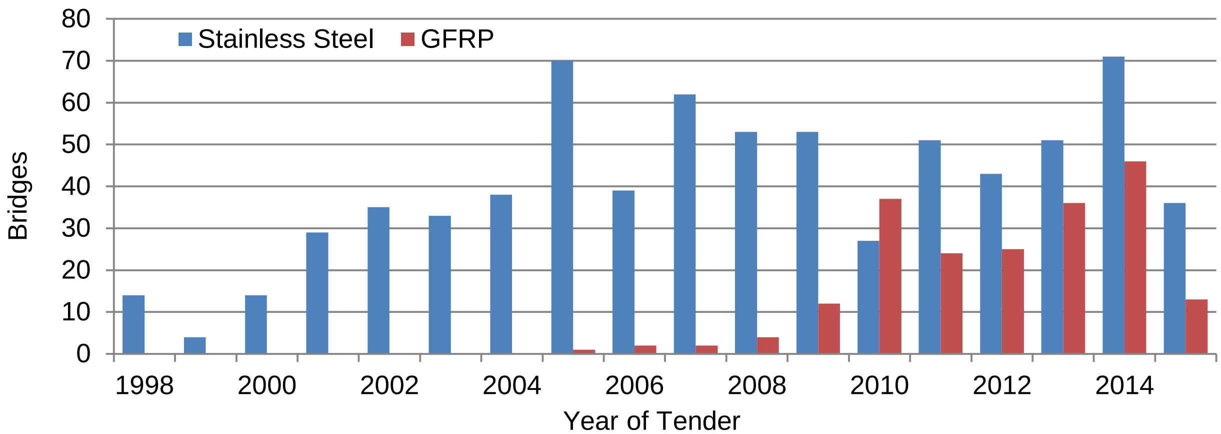

Fig. 3: Provincial bridges tendered with stainless steel and GFRP.

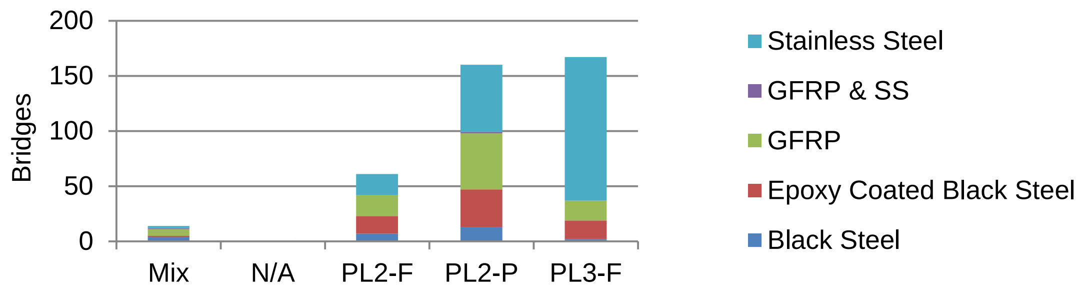

Fig. 4: Reinforcement types in new concrete barriers for contracts tendered from 2009 to 2014.

Glass Fibre Reinforced Polymer Reinforcement

Since 2005, the MTO has specified GFRP in over 270 bridges, including over 20 composite steel or concrete girder bridges with GFRP reinforcement in the deck slab and 38 bridges with

GFRP-reinforced side-by-side box girders. Fig. 3 shows the rapid increase in use of GFRP on MTO bridges in the last decade. In 2015, the MTO had three approved suppliers, but that number has grown to five suppliers in 2018. On projects with a large quantity of GFRP, the cost of GFRP has continued to decrease to not more than 30% premium over reinforcing steel, for an equivalent length of bar. A component reinforced with GFRP usually costs less than one with stainless steel. The MTO finds that high modulus grade (60 GPa equivalent) GFRP results in better economy than low modulus grade (40 GPa) GFRP, and dropped the lower modulus grade from the specification in 2017. In some applications where GFRP is governed by crack width requirements or deformability, design with GFRP requires more bars compared with steel reinforcement. GFRP design may require up to three times the number of equivalent size stainless steel bars for applications such as deck slab cantilever overhangs, pier caps, and shear-reinforcement in concrete beams. In such applications, GFRP may not be more economical than stainless steel and leads to reinforcement congestion.

Due to the differences in the interpretation of the CAN/CSA-S6-06, Canadian Highway Bridge Design Code (CHBDC) (Canadian Standards Association, 2006), there is variability in the quantity of GFRP in the deck slab of bridges designed by different structural engineers. Some designs incorporate significantly more GFRP than is structurally necessary, leading one to question whether the material’s behaviour is properly understood (Mermigas & Lai, 2014).

GFRP manufacturing processes and limits on research testing preclude its use in certain components. Limitations on the understanding of GFRP’s performance preclude its use as bent bars around corners subjected to closing moment (i.e. the corner of integral abutments or rigid frames where the reinforcement acts as a tie to resist the closing moment). The MTO is funding research to extend the use of GFRP reinforcement to this application (Sleiman & Polak, 2018) and the behaviour and detailing should be fundamentally different than steel reinforcement. While GFRP bent bars are often used for anchorage of straight bars and for anchorage of stirrups, until recently, GFRP bent bars have not been tested in closing moment corners and do not have a predictable stress-strain response at the bend since the fibres are typically deformed at the inside of the radius, because the chord length is shorter than on the outside of the radius due to the manufacturing process.

Since it is a new material, GFRP requires a design philosophy and construction practices that are different than those of reinforcing steel. Use of GFRP requires an acceptance that the problems of future generations of bridge rehabilitations will be different than the problems currently faced by engineers, and new techniques of repairing and widening bridges will be needed. Fundamentally, concrete cannot be removed from GFRP with conventional partial depth concrete removal methods (chipping hammer or hydrodemolition), and repair relies on cutting and doweling new, as opposed to chipping and splicing with existing bar. This is a natural evaluation of rehabilitation design for reinforcing steel as well. Full-depth sawcutting and doweling in new bars is a faster and more labour efficient way to connect to an existing component than concrete removal by chipping hammer followed by splicing in new bars with existing reinforcement. Full-depth sawcutting avoids micro-cracking and other challenges of chipping removals. In construction, GFRP bars cannot be field bent or easily re-ordered. Splatter of concrete on GFRP bars projecting from a deck during a concrete pour cannot be tolerated, and construction practices have evolved to include preventative measures to protect GFRP from damage, rather than relying on repairs.

Bridge Deck Waterproofing

Rehabilitation of bridges constructed in the 1980s provides an opportunity to evaluate and improve older policies. The MTO recently studied the long term performance of hot poured bituminous membrane as waterproofing for bridge decks, using chloride profiles from condition surveys of 53 bridges built between 1973 and 1986. The future ingress of chlorides was predicted statistically with Fick's Second Law of diffusion. The corrosion potential data, ranging from 6 to 12 cores per bridge, was categorized into two exposure classes. The higher exposure class consists of the perimeter, areas within 1.5 m of the barrier, curb, or expansion joints. The lower exposure class is the balance of the bridge deck. The data was separated because the perimeter has higher chloride concentrations due to poor tie-in details and ponding.

Fig. 5 shows the actual chloride concentration measurements for site 24-231, along with the model of the chloride concentration for both the end of first cycle and end of the third cycle of waterproofing.

The study proves that hot-poured bituminous waterproofing is meeting the MTO's expectations for preventing corrosion of reinforcing steel. The study showed, at a 95% confidence interval, that the concentration of chlorides at the minimum cover to reinforcement (50 mm depth) will not exceed the threshold for the initiation of corrosion at the end of the third cycle of rehabilitation, 75 to 100 years from initial construction.

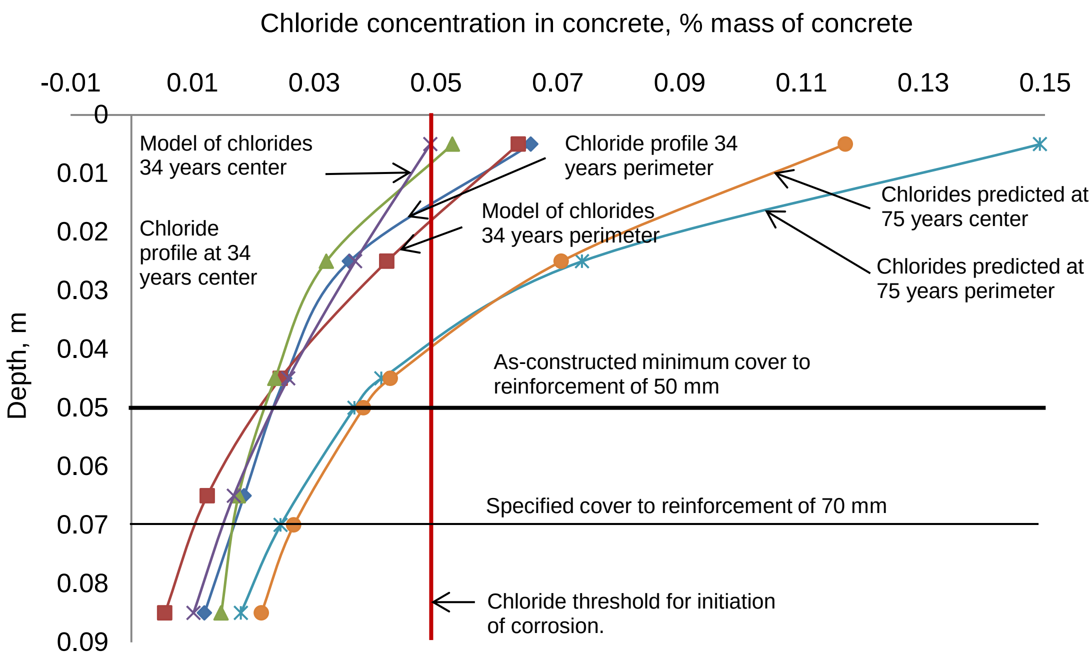

Fig. 5: Chloride penetration across waterproofing membrane (Site 24-321)

Jointless Details

Jointless details are integral to bridge design in Ontario. More than half of Ontario's provincial bridges are rigid frames or incorporate integral abutments, semi-integral abutments, integral piers, or link slabs. Collectively, the use "jointless details" represents the largest philosophical shift in bridge design in Ontario over the last two decades.

Integral and Semi-integral Abutments

Since 1993, integral abutments are preferred for new bridges subject to subsurface and geometric limitations. The soil conditions should permit a 6 m or longer pile (with a sleeve around the upper 3 m to increase flexibility), skews should not exceed 20° (although some are built up to 30°), and lengths should not exceed 150 m for concrete girder bridges and 100 m for steel girder bridges (Husain & Bagnariol, 1996). Practical limitations include a maximum wingwall length of 7.5 m, and maximum abutment height of 6 m. The MTO does not have standards for integral abutment post-tensioned bridges but has not built very many post-tensioned bridges in the last two decades. Integral abutment bridges have a lower initial cost than conventional abutments owing to fewer piles, simple formwork, and no bearings. Standard details for an integral abutment include H piles embedded 600 mm into the abutment stem, each confined locally by stirrups as shown in Fig. 6 which are designed to transfer the full plastic moment capacity of the pile to the abutment stem. Girders are supported on bearing pedestals with neoprene pads for tolerance during construction. Nearly 10% of MTO's bridges have integral abutments.

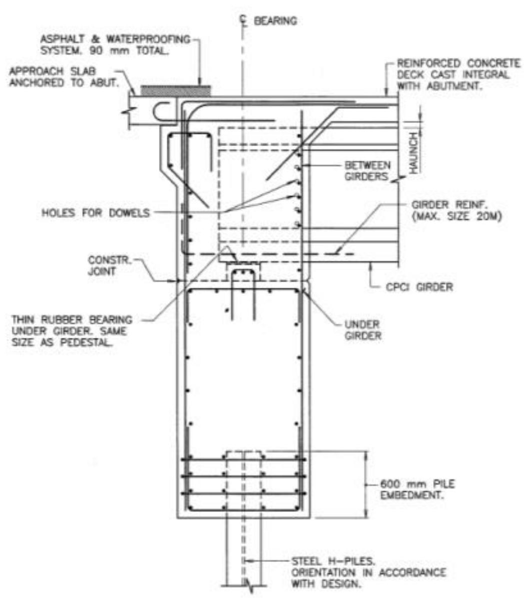

Fig. 6. Typical integral abutment detailing in Ontario

One of the first integral abutment bridges in Ontario was built in 1962. It is a four span reinforced concrete bridge with rectangular voids, 60.8 m in length, shown in Fig. 7. All three piers are monolithic with the superstructure, and each abutment is on a single row of piles with a concrete hinge between the superstructure and abutment wall. Ten similar bridges were constructed along the same section of Hwy 401. Given the excellent performance of the bridge, it is unfortunate that more were not built with this degree of continuity until 25 years later.

Fig. 7. Franklin Blvd Underpass over Hwy 401, the first integral abutment bridge in Ontario built 1962, shown with 1992 widening with cantilever brackets in front and twinning behind

Since 1999, semi-integral abutment details are preferred when integral abutments are not feasible (Husain & Bagnariol, 1999). MTO's standard details for semi-integral abutments consist of a deck end which cantilevers over the ballast wall of the abutment. The cantilevered deck end supports an approach slab. Semi-integral abutments are more costly than conventional abutments, and usually have joints in the barrier walls which leak over time, causing staining as shown in Fig. 8 and ultimately, deterioration of the wingwalls.

Fig. 8. Typical semi-integral abutments of new steel girder bridges

In 2004, the MTO released another guideline to remove expansion joints during rehabilitation by modifying the abutment and deck end to incorporate semi-integral details (Husain, 2004). The existing expansion joint and ballast wall are removed, and the deck is extended to cantilever over the ballast wall and support an approach slab, as shown in Fig. 9. Over 300 bridges have been rehabilitated from conventional to semi-integral abutment details since 2000.

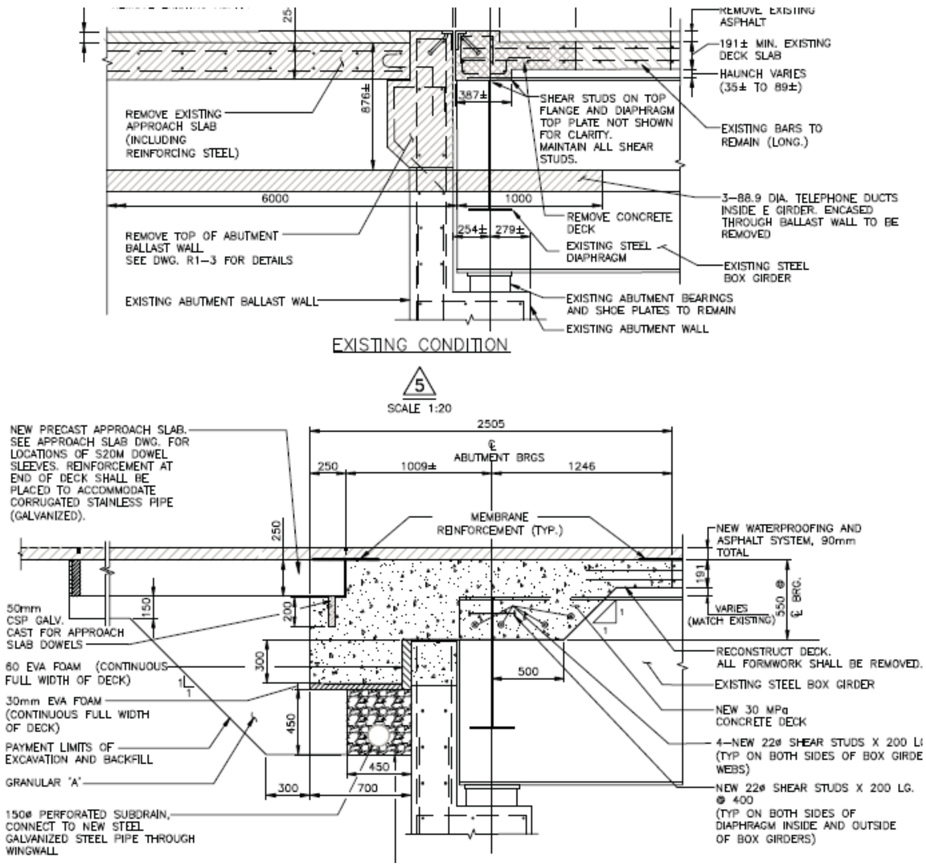

Fig. 9. Removals and new construction for conversion from a conventional abutment to a semi-integral abutment during bridge rehabilitation

Select bridges have been detailed differently with the approach slab extending over the wingwalls as shown in Fig. 10 and Fig. 11. The barriers are cast directly onto the approach slab. With the continuity of the barrier, water is contained within the roadway platform until the end of the approach slab. This detailing also facilitates widening of an existing bridge without extensive modifications to wingwalls, since the approach slab cantilevers over the existing wingwall.

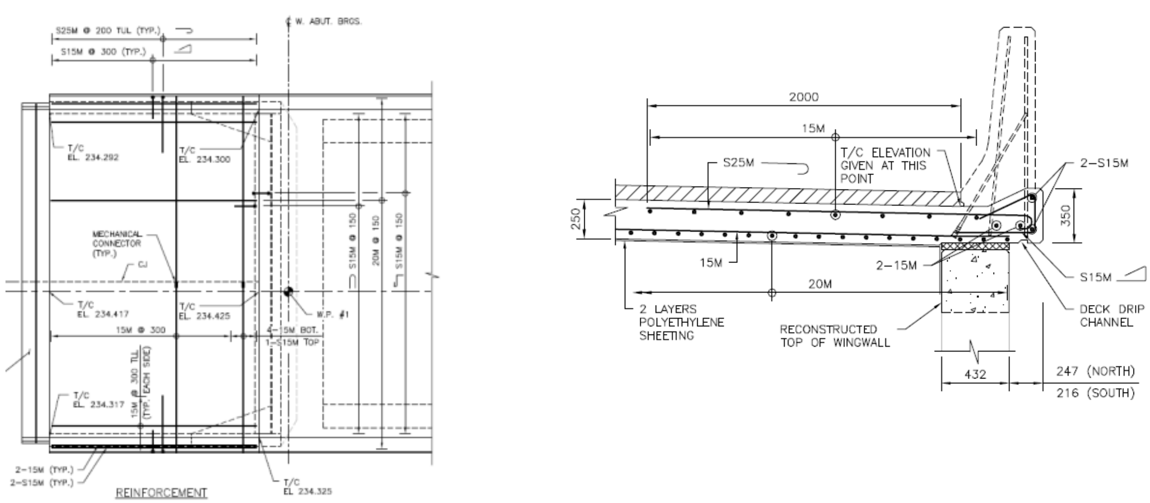

Fig. 10: Semi-integral abutment details with barriers continuous from the deck onto the approach slab and expansion joint provided at the end of the approach slab

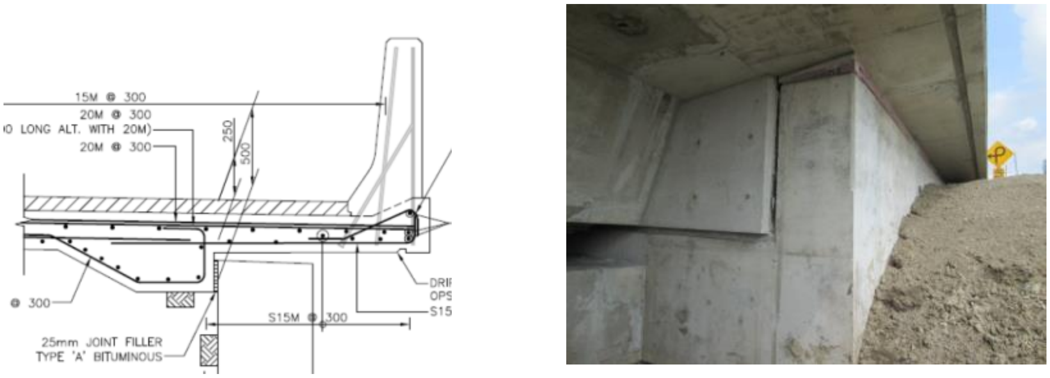

Fig. 11: Semi-integral abutment details with barrier continuous from the deck onto the approach slab which overhangs beyond the wingwall

Integral Piers

Since the 1930s, the MTO has occasionally constructed piers monolithic with the superstructure. Integral piers in slab-on-girder bridges, where the ends of the girders are completely encased in a concrete diaphragm, have been built but have not become standard despite lower initial and long-term costs. Integral piers are most often used in river crossings where a pier is founded on a single line of piles which permits a compact cofferdam, and allows ice load to be resisted through the deck acting as a horizontal diaphragm to react at all substructure locations. As shown in Fig. 12, the bridge should be nearly maintenance-free below the deck.


Fig. 12: Steel girder bridge with integral abutments and integral piers

Flexible Link Slabs

In Ontario, the flexible link design was first used in Toronto in 1987 on the Gardiner Expressway which includes a 7 km elevated viaduct built between 1955 and 1966 with over 250 concrete slab-on-steel girder spans. From 1987 to 1990, the Gardiner was progressively rehabilitated and a total of 78 flexible link slabs were built to remove three out of every four expansion joints. The good performance of the Gardiner link slabs prompted the MTO to construct a bridge with link slabs in 1996. A guideline in 2001 (Patel & Lai, 2001) recommends flexible link slabs to eliminate joints between simply supported spans where rotations across the slab are less than 0.0046 radians, skews are less than 20°, and girder depths are less than 1.2 m. Comparisons revealed the cost of the link slab replacement to be similar to an expansion joint replacement, excluding the cost of bearing modifications.

In an attempt to extend the use of link slabs, the MTO studied debonded link slabs, tested their performance in the laboratory, implemented details in a rehabilitation, and validated their performance in the field (Au, et al., 2013). The MTO has found debonded link slabs to be the most versatile, constructible and least costly means of eliminating expansion joints between simply-supported bridge spans (Lam, et al., 2008). These details provide a cost-effective means to eliminate intermediate joints between spans without making the bridge continuous for live load.

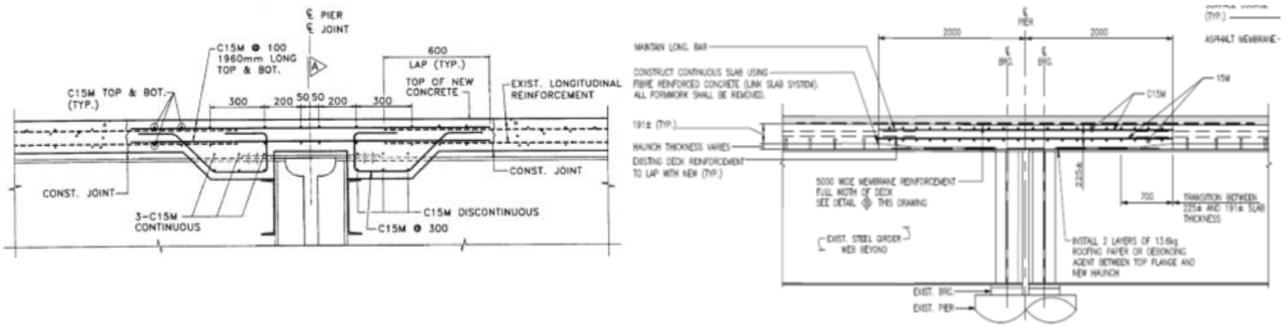

Fig. 13: Typical details for flexible link slab and debonded link slab used by the MTO

Flexible link slabs and debonded link slabs have been used on over 30 provincial bridges, most of which have been bridge rehabilitations. Ontario embraced structural continuity at the deck level in the 1950s and has a large inventory of continuous bridges without intermediate joints. Most bridges with simply-supported spans have already been rehabilitated to make the deck continuous where feasible. Nevertheless, link slabs have found a role in new bridge construction, especially for accelerated bridge construction projects where it is desirable to construct the spans in a simply-supported condition for ease of erection and then join the deck together quickly. The MTO has funded research into the use of fibre-reinforced concrete in link slabs to reduce reinforcing steel and control crack width in service. Future development of the debonded link slab concept will improve performance and durability, but the link slab practice is well-established in Ontario.

Expansion Joints

The MTO almost exclusively uses strip-seal expansion joints anchored in steel armouring angles in concrete end-dams. Strip seals are rubber with minimum 6 mm thickness, anchored in press-fit steel sections or clamped down with steel retainer bars. Expansion joints are installed after paving of the asphalt for a smooth ride and longevity. Epoxy injection under the armouring angles seals any voids caused by lack of concrete consolidation. Some strip-seal expansion joints allow up to 75 mm of movement. The expansion joints are detailed to last the full cycle until rehabilitation, between 25 and 35 years, although the rubber joint seal may require replacement at a shorter interval. Integral and semi-integral abutments are detailed with the expansion joints installed at the end of the approach slab for movements greater than 10 mm. A sleeper slab anchors the fixed end of the joint as shown at the right side of Fig. 14, and also supports the end of the approach slab. For movements less than 10 mm, the approach slab terminates and the asphalt is saw-cut full depth and filled with hot-poured rubberized compound.

Fig. 14: Expansion joint at the end of an approach slab

Despite the design guidelines at an engineer's disposal, the MTO does not have a formal policy or process to lead the engineer to conceive a bridge with a high level of continuity. There is a perception in practice that semi-integral abutment details are as good as integral abutments, whereas experience indicates that integral abutment and rigid frame bridges have the lowest maintenance and rehabilitation costs. In recent new highway sections constructed through public-private partnerships, many bridges have been built with conventional abutments on high skews with large retained soil system walls. Experience with rehabilitations indicates these bridges will have higher than necessary maintenance needs in the 50 to 60 year horizon.

Prefabrication

The MTO has routinely used precast concrete I-shaped girders and voided box girders (1200 mm wide) since the 1960s. Since 2000, the MTO has made a concerted effort to extend prefabricated construction to other components such as including deck, curbs, approach slabs, pier caps and abutments (Husain & Lam, 2006). Two main factors are the impetus: increased quality and durability (which is tied to materials availability in remote areas) and reduced construction duration. Close to urban areas where good quality cast-in-place concrete is readily available, prefabricated components are used primarily to accelerate construction and reduce impacts to traffic, without sacrificing quality. In remote areas of Ontario, the impetus for prefabrication is the lack of proximity of local ready-mix concrete which has, on average, led to lower quality of cast-in-place construction. Prefabrication is one solution to the lack of materials availability. The MTO has therefore pursued different prefabricated systems depending on a bridge's location.

Lower user costs, less traffic disruption, improved work zone safety, lower environmental impacts, improved constructability, and lower life cycle costs are touted as other advantages of prefabrication but are rarely the driving factors on typical projects. In cases where user costs and traffic impacts are severe, the superstructures have been completely prefabricated and lifted or slid into position. The MTO has completed 10 such rapid bridge replacements since the first in 2007. The construction cost is approximately double the cost of other prefabricated bridge systems and is therefore justifiable only when the bridge carries very high traffic volumes which cannot be detoured (typically average annual daily traffic in excess of 100 000 vehicles).

Precast Superstructure

The precast superstructure systems used by the MTO can be broadly classified into four systems.

1. Full-depth precast concrete deck slab on steel or concrete girders. The deck slab is constructed to the full or half-width of the bridge with joints running transversely across the deck. The slab is made composite with the girders by arranging the shear connectors in shear pockets at regular intervals for transverse slab elements.

2. Side-by-side precast concrete box girders. The girders are placed side-by-side and span longitudinally from one end of the bridge to the other. The boxes are connected with shear keys between them, or with a composite cast-in-place topping slab cast on the girders. The boxes are nominally 1200 mm wide and range in depth from 600 to 1200 mm. The sections are voided with a block of EPS which functions as a lost form.

3. Steel or concrete girders with precast composite slab. The bridge is subdivided in T or U-shaped composite slab-on-girder elements (decked girders) that span between bridge supports and are connected together with longitudinal cast-in-place concrete closure strips. Sweep (lateral deflection in the plane of the deck) and relative elevation differences have consistently been a problem for T shaped girders. Chains and temporary diaphragms are required to bring the deck slab of adjacent T girders into alignment. Composite U shaped girders are considerably more stable during transportation and handling. A practical weight limit of 100 tons is used for ‘supermodules’.

4. Partial depth precast concrete deck panels spanning transversely between girders, and topped with a cast-in-place concrete layer to achieve the finished deck thickness. The MTO has used partial depth deck panels since the mid-1990s and introduced standards in 2005. The panels are 90 to 110 mm thick, pretensioned concrete, and work with steel and concrete girders spaced up to 4.0 m-centre-to-centre.

An analysis of bridges tendered from 2009 to 2014 indicates 20 bridges with full-depth precast deck on girders, 69 with side-by-side box girders, one bridge with steel girders composite with the deck slab (supermodules), and four bridges with partial depth precast deck slabs. Partial depth precast panels have however been used extensively in public-private-partnership projects to reduce construction duration and on-site labour associated with deck forming and stripping. MTO may also accept partial depth precast panels to be used in place of a cast-in-place deck slab when proposed by the Contractor. Of the systems discussed, the largest total deck area has been constructed with this method.

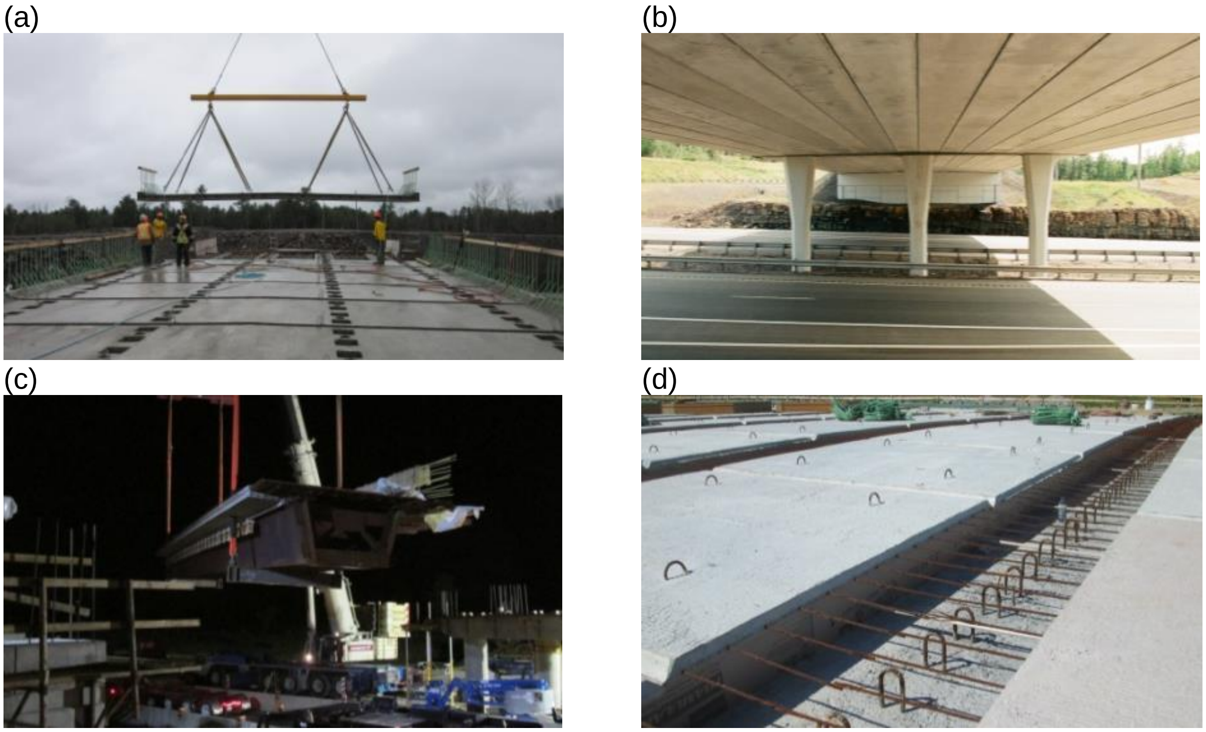

Fig. 15: Prefabricated superstructure systems in Ontario. (a) Precast concrete deck on girders; (b) side-by-side precast concrete box girders; (c) steel girder with precast composite concrete deck and (d) partial depth precast concrete deck panel on girders

The MTO has built increasingly more side-by-side box girder bridges in the last 10 years. Of the precast concrete girder bridges tendered from 2009 to 2014, 69 were side-by-side box girder bridges and only 34 were slab-on-girder bridges. Perceived advantages of side-by-side boxes are a shallower depth (relative to typical precast I girder systems), simple design, good aesthetics owing to a smooth soffit, span-to-depth ratios of up to 42, and the ability to completely eliminate forming a deck. The advantages come at a cost. Inspection of bearings at the ends of the box girders is limited at abutments and piers where the box girders are placed end-to-end. Placed side-by-side, the webs between girders cannot be inspected. Similar to cast-in-place voided slab bridges, the condition of the voids cannot be known without destructive testing. Additionally, they have high material and labour input, owing a high form ratio (one web per every 0.6 m of bridge width) and complex assembly. The labour required of a precaster to produce a box girder is approximately 2.5 times greater than for a precast I-girder and the total labour for girders and deck is also higher than a concrete slab on concrete girder system. The system is not amenable to mass production. There are ancillary costs associated with a larger number of bearings (typically 4 times as many as a slab-on-girder bridge) and larger number of individual bearing pedestals at the abutments.

For many reasons, full-depth deck panels and supermodules should be preferable to the side-by-side box girder systems. Transverse joints are preferable to longitudinal joints because the main deck slab function design is transverse, there is less total length and area of joints (for a given deck area), the positive moment regions are compressed across joints, the weight of individual components is kept down, and challenges with cambers and sweep of adjacent elements is avoided. There is opportunity with full depth deck panels to further reduce the number of longitudinal elements and thereby reduce the number of shear pockets where composite action is to be achieved.

Supermodules show the greatest promise for accelerated bridge construction at a marginal cost relative to traditional practices. The Westminster Drive Underpass over Hwy 401, a two lane bridge with integral abutments and integral pier pictured in Fig. 16, was constructed in 40 days and cost 29% more than a nearby bridge replacement with conventional methods which required one year and half. The concept is simple, scalable, offers the fewest cast-in-place connections relative to other prefabricated systems, has the potential to capture structural efficiency of shored construction, could be standardized, and does not sacrifice aesthetics (compared to conventional construction in Ontario).

Fig. 16: Westminster Drive Underpass over Hwy 401

Precast Substructure

Precast pier caps have been used on several projects with little advantage over cast-in-place construction, when ready-mix concrete is available locally. In most cases, precast piers have been designed to mimic cast-in-place construction resulting in heavy components which require large cranes to install. Bearing seats were cast into the precast components, providing low tolerance for placement on cast-in-place concrete columns. Successful applications have sought to limit the depth of the pier cap, use pretensioned prestressing strand to prevent cracking of the concrete during handling, and allow bearing pedestals to be poured on site for tolerance.

The MTO has constructed some integral abutment bridges with precast abutments. Prefabricated segments are placed, braced temporarily, and joined together with vertical cast-in-place closure pours. Each precast abutment segment is supported on at least two piles for stability, and sleeves are provided to slide the segment over the top of the piles and embed them in the segments. Girders are installed and joined to the abutment with a cast-in-place connection encasing the ends of the girders. As with pier caps, the weight of this precast abutment design is substantial. The lack of repetition of typical segments in precast abutments, combined with heavy weights, and cast-in-place concrete closure pours which exceed 20% of the total concrete in the abutments contributes to high costs for these components.

In Northern Ontario, one approach is to minimize the abutment by disassociating the horizontal support function of the abutment (earth retention) from the vertical support function of the abutment. Sheet piles or retained soil system (RSS) walls retain the earth backfill, which the abutment seat is reduced to the size of a pier cap with the sole function of supporting the girder ends. The approach slab is supported directly on the girder ends.

(a) (b)

Fig. 17: Two approaches to prefabricated abutments: (a) precast concrete components emulating a cast-in-place abutment and (b) example of semi-integral abutment with girders supported on pier cap on piles and earth retained by separate sheet pile retaining wall system

Ultra High Performance Fibre Reinforced Concrete (UHPC) in Precast Construction

Cast-in-place joints have been a weak link of older precast bridges. UHPC is useful for joining precast components owing to its durability. The MTO has used UHPC in this application on 79 bridges tendered between 2006 and 2015. In most cases, the material properties of UHPC are used to reduce reinforcement lap length, and thus reduce the width of closure strips. The adequacy of details used in closure strips with GFRP dowels is a subject of debate and further study within the MTO. Cost for UHPC closure joints ranges between $500 and $1200 CDN per linear metre of joint. Excluding major river crossings, the average cost of UHPC has been around $200 000 CDN on a typical project. The total UHPC tendered by MTO up to 2015 was $21 million CDN, based on the average of the three lowest bids.

Conclusion

Bridge longevity is integral to bridge design practices in Ontario owing to lessons learned through a history of rehabilitation. A corrosion protection policy prescribes the minimum level of detailing for durability on routine bridges and always includes waterproofing of bridge decks. A recent study validates that the current waterproofing system will ensure a service life of 100 years for bridges constructed since the 1980s. Premium reinforcement such as stainless steel and GFRP is used increasingly in concrete components exposed to de-icing salts. Over the last two decades, the MTO has issued guidelines to increase the use of continuity and jointless details in new construction and rehabilitation. Recent trends indicate that use of prefabrication is increasing in order to accelerate bridge replacement. As demonstrated with the guidelines for jointless details, standards can be a successful means of promoting the right systems and design details.

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