The Future of the Champlain Bridge

Prepared for:

The Jacques Cartier and Champlain Bridges Incorporated

Prepared by:

Delcan

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Dear Sir

RE: THE FUTURE OF THE CHAMPLAIN BRIDGE

We are pleased to submit our Report on The Future of the Champlain Bridge.

Yours truly,

W. Victor Anderson, P.Eng.
Executive Vice President

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Enc. Report - The Future of the Champlain Bridge

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EXECUTIVE SUMMARY

Delcan was retained in August 2010 by The Jacques Cartier and Champlain Bridges Incorporated to carry out a Structural Health Assessment Study of the Champlain Bridge.

The objective of this contract was the undertaking of a study in order to provide the Corporation with an expert assessment of the current structural health of the Champlain Bridge.

This Report – The Future of the Champlain Bridge Crossing, records Delcan's assessment of the future of the Champlain Bridge Crossing based on work carried out by Delcan in 2010.

The work covered the deck, superstructure and substructure of the main sections of the bridge, namely, Sections 5, 6 and 7 which include:

- Section 5, the section extending from Île des Soeurs to the steel structure of the bridge and comprising prestressed concrete girders integrated with deck infill sections and diaphragms which are transversely post-tensioned to the girders.
- Section 6, the bridge section spanning the St. Lawrence Seaway and including the main span which consists of a cantilever-type through truss steel structure and the flanking deck-truss approach (transition) spans, and
- Section 7, located between the steel structure of Section 6 and the abutment on the South Shore and including prestressed concrete girders integrated with deck infill sections and diaphragms which are transversely post-tensioned to the girders in a fashion similar to that incorporated in Section 5.

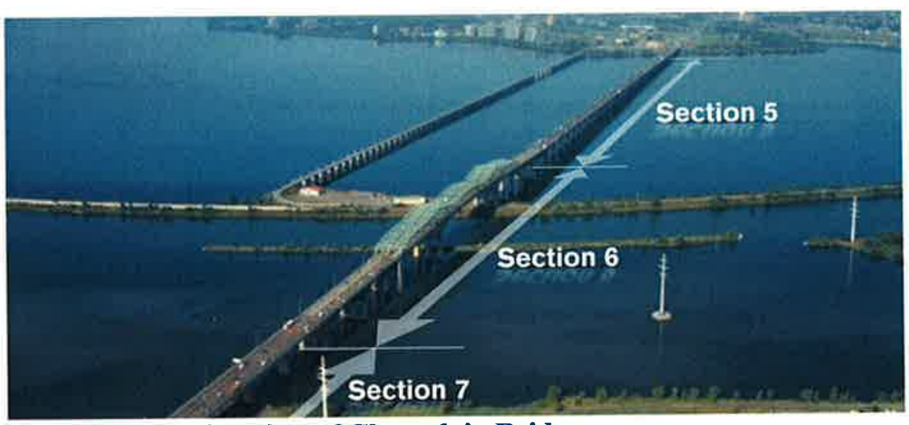

Figure E1 - Aerial View of Champlain Bridge

This report is based upon works carried out by Delcan which include a review of the bridge in the field, and a review of extensive records, reports and studies provided by the Corporation as to the history of the various interventions on the bridge since its construction.

This Report – The Future of the Champlain Bridge, comes to the following conclusions:

- The Champlain Bridge is a major crossing of the St. Lawrence River between Montreal and the South Shore. Completed in 1962, it carries heavy vehicular, truck and bus traffic and is a critical link in Montreal's transportation system.
- The Champlain Bridge is designated as a lifeline bridge. This has implications as to its required behaviour under seismic loading. The current bridge is not compatible with a lifeline designation.
- It is understood that the bridge is functionally deficient in respect of current traffic and transit demands as well as traffic and transit demands expected in the medium and long term.
- The bridge segment under study here comprises three sections, namely the main span section (Section 6) which crosses the St. Lawrence Seaway by means of a structural steel bridge section, and two prestressed concrete approach sections (Sections 5 and 7) comprising 50 spans in total.
- The structural steel superstructures (Section 6) are in relatively good condition. While these structures provide some structural redundancy, they are not considered to have a large excess of live-load carrying capacity. The orthotropic steel deck on the main structure has however improved the live-load carrying capacity as well as its rigidity and durability.
- The reinforced concrete substructures supporting the structural steel superstructures are considered to be in fair condition. Extensive repair works are being carried out on these substructures. These repairs do not, however, include seismic rehabilitation or retrofit.
- The main span, Section 6, structures have not been originally designed for seismic loads corresponding to current seismic requirements for a lifeline bridge.
- The approach spans, Sections 5 and 7, comprise prestressed concrete girders integrated by means of transverse post-tensioning with deck infill sections between the girder flanges and with diaphragms between the girders, the entire assembly comprising an orthogonally-stressed grillage of concrete. This superstructure scheme was the least expensive of some 28 alternatives to the original design. These alternatives were proposed by contractors and the least costly one was accepted for implementation. In conjunction with this superstructure scheme, a compatible substructure system comprising pier caps, pier stems, and circular foundations founded on bedrock, was also developed for construction.
- The approach spans were not designed for seismic loading corresponding to current seismic loading requirements for a lifeline bridge.
- Analyses have shown that the capacity of the bridge to carry wind loading is marginal.
- The bridge was not designed to be resistant to corrosion and/or concrete degradation which would be caused by salting of the bridge. In the initial years of its service, we understand it was not salted but soon thereafter salting of the bridge commenced. In consequence, the bridge has now suffered some significant deterioration of the concrete and steel which comprise the bridge, particularly on the bridge approaches where both the superstructure and the substructures have been adversely affected.

- The bridge has been the subject of a methodical inspection, investigation, testing, analysis, repair and rehabilitation programme under the auspices of The Jacques Cartier and Champlain Bridges Incorporated. This programme continues in place and currently is programmed for 10 years at a cost of some $212 Million with the continuing necessary inspections, investigations, testing, analyses, repairs and rehabilitation required to manage the risks associated with maintaining the bridge safely in service during that time frame. In this context, works are currently underway on the bridge including rehabilitation of pier caps, for example, augmenting the works carried out on other elements of the bridge including strengthening of the edge girders of the approach spans by means of the addition of external post-tensioning. We understand that this external post-tensioning programme may be expanded to include all of the edge girders on the bridge, a total of 100 such girders, in the context of a 10-year programme and on a priority basis depending upon the condition of the girders.

- As is common with the type of deterioration which is observed in the edge girders and in many other elements of the bridge, it can be expected that deterioration will progress at an increased rate which is characterized by an exponential curve, as time goes by.

- Because all of the rehabilitation works which would be necessary to rehabilitate the bridge cannot be carried out instantaneously, there are and will continue to be risks associated with the operation of this bridge. These risks are being managed in the context of a methodical programme and have been carefully studied by The Jacques Cartier and Champlain Bridges Incorporated. Nevertheless, the risks cannot altogether be quantified and some unknowns are associated with them. For example, because the actual condition of the post-tensioning steel in the prestressed girders cannot altogether be quantified and there is evidence of broken wires and broken tendons in some of these girders, some unknown risks are associated with these elements.

- Analyses have suggested that the loss of an edge girder in the approach spans could result in the progressive collapse of the span.

- The repairs and the restoration of load-carrying capacity being incorporated in the edge girders are considered to be appropriate given the condition of the girders and given the virtual impossibility of replacing the girders as a result of their highly-integrated construction with the diaphragms, with the deck infill panels, and with adjacent girders, to all of which they are connected by high-strength prestressing steel. The addition of external post-tensioning is considered to be an economical methodology for adding to the load-carrying capability of the bridge edge girders on the approach spans, and to reducing risks over the relatively short term. Such post-tensioning is not considered compatible with long term service as it is exposed to the elements and is attached to the structure of the girders in a way which is not equivalent to new construction inasmuch as, in part, the attachments must be made to girders which have themselves already suffered some deterioration.

- Life cycle costing studies have shown that the cost of maintaining the bridge in service in the order of 15 years, that is, the relatively short term, and then replacing it with a new bridge, is virtually the same as the cost of maintaining the existing bridge in service for some 50 years. This is an unusual finding in the context of a bridge in reasonable condition and it suggests that this bridge is in very much poorer condition than would be typical for bridges of its age and importance. It suggests also that the costs of maintaining this bridge in service will be very large while, at the same time, risks associated with maintaining the bridge in service cannot altogether be eliminated and will almost certainly be greater than the risks associated with a new bridge.

Our impression of this bridge is that it has many deficiencies, some of which are very significant and that its continued operation in service, even in the context of the methodical and organized inspection, testing, analysis, rehabilitation and repair programme which is underway, entails some risks which cannot altogether be quantified.

The deficiencies and associated risks are such that the Champlain Bridge should be replaced by a new crossing and an expedited process to accomplish this should be implemented as soon as possible.

In the meantime, the current rehabilitation programme should continue.

1. DISCUSSION OF BRIDGE CONDITION AND IMPLICATIONS FOR REHABILITATION

The various elements of this major bridge crossing vary in condition from 'good' to 'deficient'. There are significant portions and elements of the bridge which are in a condition that might be described as 'satisfactory' in the context of its service life to date of 48 years. Amongst these, one finds the structural steel main span, the structural steel deck trusses, the orthotropic steel deck on the main span (which is about 17 years old), and portions of the reinforced transversely post-tensioned deck/girder system which comprises Sections 5 and 7. These are significant elements and a significant percentage of the total bridge structure and hence an early impression of the bridge might be that it could be rehabilitated if appropriate measures could be found to deal with the deterioration which exists in the other elements of the bridge while, at the same time, maintaining traffic in service to a satisfactory degree. The structural steel in the main span structure, for example, weighs some 11,000 tons and a very considerable investment has been made by Canada in its original construction and in maintaining it since its entry into service, in addition to a major rehabilitation effort involved in replacing the original reinforced concrete deck with an orthotropic steel deck with consequent significant benefits to this bridge section.

Figure 1 - The Cantilever-Type Steel Truss Bridge

Figure 2 - Prestressed Concrete Girders and Reinforced Concrete Piers

At the same time, many elements of the bridge are in a condition which may be described as 'poor' to 'deficient'. These include such elements as (possibly) the underwater portions of the foundations, the pier stems, the non-repaired pier caps and crossbeams, the prestressed concrete edge girders in Sections 5 and 7, the ends of the prestressed concrete girders in Sections 5 to 7, the expansion joints, the non-repaired bearings in Sections 5 and 7, and ancillary elements. As well, there are localized defects in such elements as the transversely post-tensioned concrete deck in Sections 5 and 7, and some evidence of deterioration of some of the transversely post-tensioned concrete diaphragms in Sections 5 and 7.

Given this variability in condition, it appears that a rehabilitation programme geared to keeping the bridge in service in the long term could be envisaged from a theoretical perspective but there are practical considerations which make this quite difficult, if not impossible, when combined with considerations of maintaining traffic on the bridge and also taking into account more global structural deficiencies in the bridge which cannot be seen but which must be calculated and which include the deficient seismic capacity of the bridge.

When all of these factors are considered, the rehabilitation of the bridge to carry traffic safely in service in the long term, while respecting the current requirements for maintaining the bridge traffic carrying capacity during rehabilitation construction works, is likely to be a very costly, lengthy and difficult process which in and of itself involves considerable risks. These risks essentially relate to the fact that the deterioration of the bridge which is currently observable and which has been documented in detail by others, is considered to be progressing at an exponential rate, and therefore the risks to the bridge are increasing as time passes by. These risks are currently being managed by a programme of prioritized repairs and rehabilitation works which are scheduled to be implemented over a 10-year period currently in the second year of the programme. Implementation of a programme of works which would bring the bridge up to modern standards from functional and structural perspectives including seismic capacity would be so extensive that, in conjunction with attempts to maintain traffic on the crossing throughout construction, the duration of construction would be such as to cause the integrity of the crossing to be at increased risk over a lengthy period of time.

2. DISCUSSION OF CURRENT REHABILITATION PROGRAMME

The current rehabilitation programme as we understand it, comprises a series of steps amongst which are:

- Protection and paving of the bridge deck.
- Replacement of median barrier.
- Replacement of bearings.
- Replacement of all expansion joints and reconstructing the ends of the deck slab.
- Repairs and strengthening to the prestressed concrete edge girders including concrete repairs and the addition of longitudinal external post-tensioning, and a queen-post system to improve moment and shear capacity.
- Repairs to the pier caps including the addition of post-tensioning.
- Repairs to the pier stems.

- Other repairs to the diaphragms and other elements of the bridge.

All of these repairs have been carried out in conjunction with an ongoing planned programme.

The nature of this rehabilitation programme is that it has been envisaged in the context of a 10-year undertaking designed to maintain the bridge safely in service over a 10-year period from 2009 to 2019 and, it is hoped, for a limited period somewhat beyond that date. The repairs are extensive and substantial but they are not repairs which are compatible with, for example, extending the life of the bridge another 50 or more years. The addition of external post-tensioning to the girders, for example, necessarily involves a post-tensioning system which is exposed to the elements to some extent despite the efforts to protect it, and includes anchorages which are themselves post-tensioned on to the existing deteriorated prestressed concrete girders, a less than ideal situation. It would clearly be better from the standpoint of long-term durability if the deteriorated external prestressed concrete girders could be replaced altogether but that is virtually impossible without completely replacing the approach span superstructures altogether where deterioration at the edge girders is a concern. In order to be compatible with a new 50-year service life, virtually the entire superstructure on Section 5 and 7 would have to be replaced to eliminate the deterioration, damage and chloride ion-affected concrete which is the Achilles Heel of these superstructures, which generally is located in the external prestressed concrete girders and in the ends of the prestressed concrete girders.

The substructure repairs which are currently being carried out similarly are designed using the same philosophy. For example, the substructure rehabilitation is geared to removing as much deteriorated concrete as is reasonably possible given the fact that the bridge is in service carrying traffic loads and that the substructure load-carrying capacity cannot be unduly compromised during the course of the rehabilitation works. At the same time, the penetration of chloride ions into the concrete is very significant and the deterioration of concrete and reinforcing steel which has been observed in the course of repairs to date has, we gather, been so significant that it is not possible to remove all of the observably-deficient concrete without putting at risk the superstructures which are supported by the substructures being repaired.

Figure 3 - Repairs to Reinforced Concrete Pier Cap Beams

In addition, there is some concern with regard to alkali aggregate reaction in this concrete. These two factors mean that short of the entire replacement of the piers, including the pier stems and the pier caps as well as the pier crossbeams in the main spans, some deficient or degraded concrete will remain as a part of the rehabilitated structure. This is considered to be compatible with a relatively short-term service life in the order of 10 years but not with long-term service lives in the order of 50 years or more.

The fact that this is considered to be a lifeline bridge, whereas it does not have the seismic capacity compatible with that designation, is another factor in the consideration of the appropriate rehabilitation methods for the bridge in the context of short-term and long-term service. It is clearly not reasonable to attempt to improve the seismic capacity of the bridge to be compatible with its lifeline designation in accordance with current codes if the bridge is anticipated to be in service for a relatively short time such as 10 years. Accordingly, such modifications are not being contemplated at this time. In the context of a much longer service life, the seismic capacity would have to be improved to be compatible with the requirements of a lifeline bridge. This would be a very significant undertaking which would require significant modifications to the bridge including augmenting the capacity of the foundations, replacing or significantly modifying and strengthening the pier stems, crossbeams and capbeams, the probable use of seismic isolation devices to dampen seismic loads, the use of restrainers to prevent span unseating, and the replacement of the deck superstructures on Sections 5 and 7. The extent of works involved in modifying the structural steel in the main span to accommodate seismic loads compatible with performance of the bridge as a lifeline structure may also be a significant undertaking. In summary, the works required to improve the seismic capacity of the bridge to be compatible with the designation of the bridge as a lifeline structure are so significant that they are far beyond the scope of the rehabilitation programme which is currently being implemented, and which is envisaged in the context of a 10-year programme geared to maintaining the bridge in service over the relatively short term.

We observed some of the rehabilitation works which are being carried out in the context of this programme at this time including in particular repair of the pier caps on the approach spans and repair of the main pier crossbeams on the main span. We also observed rehabilitation works involving the addition of external post-tensioning to the prestressed concrete girders on the approach spans, additional shear reinforcing to the prestressed concrete girders on the approach spans, and paving works which were underway on the bridge.

Figure 4 - Repairs to Prestressed Concrete Girders including External Posttensioning

While there are a number of significant deficiencies in the bridge, the most significant and complex to manage is the deterioration of the edge girders in the prestressed concrete grillage spans which form the approach spans in Sections 5 and 7. A series of steps has been taken over many years with a view to inspecting, analyzing, understanding and dealing with the deterioration which these girders have experienced. Steps which have been taken include improving the drainage system on the bridge so that salt-laden water is not directed from the bridge deck onto the surfaces of the girders, the application of coatings with a view to protecting the girders from salt-laden water, the addition of external post-tensioning including horizontal post-tensioning to deal with deficiencies in bending moment and inclined post-tensioning to help deal with deficiencies in shear capacity, concrete repairs including the replacement by patching of concrete lost from the girder webs, local addition of external stirrups, and replacement of the bearings which support these girders and the entire superstructure on Sections 5 and 7.

The understanding of these girders has been the subject of a considerable amount of work including inspection, investigations, field measurements, examination of the loss of post-tensioning wires and tendons, consideration of the deficiencies in the grout which was used originally to grout the tendons into position within the girders, magnetic post-tensioned tendon investigations, assessment of the precompression currently provided to the prestressed concrete girders by the remaining post-tensioning, evaluation of the king post option for girders in Section 5 where deterioration of the edge girders is most significant (these king posts are also known as queen posts in other documentation on the bridge), testing of the strength of concrete, and some Structural Health Monitoring works, amongst other investigative techniques.

Figure 5 - Repairs to Prestressed Concrete Girders Including Queen Posts and External Post-Tensioning

The pier caps are also of significant concern and hence they are being repaired and reinforced on a high priority basis.

The current rehabilitation scheme is considered to be compatible with a relatively short-term horizon, i.e., in the order of 10 years. However, it does of necessity involve continuing risks, as the structure cannot be instantaneously repaired everywhere, and the condition of some components cannot be completely known or defined.

3. LONG TERM REHABILITATION TO SUSTAIN THE EXISTING CROSSING

We have considered, based upon the understanding gained by review of the existing documents, the possibility of developing a long-term rehabilitation strategy which would be appropriate for sustaining the existing crossing for the next 50 years.

The first question which would be asked in the context of such a long-term rehabilitation strategy is whether or not the existing bridge has the functional characteristics necessary to an appropriate level of service as is anticipated to be required over the next 50 years. Complications originating from the operation of the reserved bus lane involving contraflow traffic with no divider, suggest that there are some functional limitations associated with the existing bridge. This also makes re-routing heavy trucks to the interior lanes (away from the deteriorated edge girders) impractical and/or problematic from a risk management perspective, as noted in the Request for Proposals.

From a structural perspective, there is a significant number of deficiencies which would need to be addressed in the context of any possible programme of long-term rehabilitation to sustain the existing crossing for 50 years. These are so substantial that they would include, we believe, such elements as:

- Strengthening of the existing foundations.
- Significant strengthening of the pier stems.
- Significant strengthening and modification of the pier caps.
- Extensive repairs to the main span piers including crossbeams.
- The incorporation in the structure of seismic isolation devices and restrainers.
- Complete replacement of the superstructures on Section 5 and 7.
- New bearings.
- New expansion joints.
- New waterproofing and paving.
- New barriers.
- New ancillary works such as lighting and the drainage system.
- Possible significant works related to the seismic capacity of the structural steel main span given that it was not originally designed for significant seismic loads and that the bridge is considered to be a lifeline structure which must remain in service after a 475 year return period earthquake, and which according to its designation must be open to emergency vehicles after a large earthquake event with a 1000 year return period.
- Ensuring that the structural steel spans are not prone to fatigue and that the structural steel design and detailing has been appropriate with regard to fatigue.

Such works are so extensive that it is very difficult if not impossible to envisage their being completed while the bridge carries traffic, without a very significant cost premium and without a very significant penalty in terms of duration of construction compared to construction works which could be completed on a new bridge alongside the existing bridge.

As well, many of the steps which would be taken in the context of such a significant rehabilitation scheme would temporarily expose the bridge to more risk. For example, when foundations are exposed to enable them to be augmented and strengthened, the bridge is at somewhat more risk than it is currently.

A key issue in the context of such an extensive rehabilitation scheme and desired continued service life of 50 years is the nature and condition of the superstructures and spans in Sections 5 and 7. These are highly integrated prestressed post-tensioned grillage structures essentially comprised of girders, deck infill sections and diaphragms, stressed orthogonally, comprising single integrated units for each span. We have attempted to envisage schemes whereby the deteriorated external girders could be strengthened or replaced in such a manner as to be compatible with sustaining the existing crossing in service for 50 years while, at the same time, permitting traffic to remain essentially in service during rehabilitation works, and while at the same time not compromising the integrity of the spans given their integrated nature. It can be appreciated that there are difficulties with virtually every scheme that can be envisaged in this regard including for example:

- Structural steel girders placed outside the existing exterior girders involve additional bending moments on the pier caps and are difficult to integrate with the existing prestressed post-tensioned integrated concrete system which forms these spans.

- Structural steel girders placed inside the edge girders interfere with the transverse diaphragms.

- Various I-girder and box girder configurations interfere with the transverse diaphragms.

- The removal and replacement of the existing edge girders affects the prestressing and post-tensioning loads in the rest of the span, with possible adverse affects including potentially the collapse of the span.

- Removal of the edge girders involves detaching them from the diaphragms and from the deck. This is difficult in the case of the diaphragms as the diaphragms are post-tensioned through the girder webs. It is also very difficult in the case of the deck as the deck and top flanges of the girders are post-tensioned together to form a single deck slab in effect. It is possible that some very elaborate compensating methodology may be developed to deal with the various load effects induced in the overall span by the removal of such key element as the edge girders but we cannot envisage a practical system for doing so, particularly in the context of the bridge carrying traffic.

Some of the exterior girders are so significantly deteriorated that one can see the ducts which contain the high-strength steel tendons, as a result of cracking in the exterior girder webs located at the ducts. This is something which is unique in our experience. It is believed that the grouting which was used in these ducts originally may have frozen and there is considerable concern with regard to the quality of the grout that was used in the ducts. This is an issue that should not be forgotten in assessing the interior girders as well. This kind of deterioration combined with the other more generalized deterioration, the loss of the high-strength tendons in some of the girders, and the corrosion and concrete deterioration which is evident, suggest that some of these girders are beyond repair in the context of a long service life, particularly in the context of concrete which is not air entrained in accordance with current standards for durability. The repairs which are being applied to these girders including external post-tensioning to provide additional bending and shear resistance, are compatible with reducing risk but the degree of reduction of risk must remain unknown as, despite detailed efforts to assess the condition of the cables and the condition of the precompression remaining in the girders, some doubt must remain as to the actual condition of the girders even after all of the requisite repairs are carried out and the external post-tensioning is applied. For this reason, it is appropriate to consider Structural Health Monitoring, as has been done to some extent here but, at the same time, it is possible that even with Structural Health Monitoring, given the condition of these girders, the first signal from the Structural Health Monitoring system as to difficulties on the bridge may not occur until the difficulties are severe enough to cause safety issues to arise on the bridge.

Figure 6 - Web of Prestressed Concrete Girder with Tendon Partially Visible

It is interesting to note that a bridge with a very similar construction configuration and located in Belgium suffered damage similar to that which has been sustained by the Champlain Bridge, and consideration was given at that bridge to a range of methodologies for rehabilitating the bridge superstructure spans. In that case, the decision was ultimately made that it was not possible to carry out such rehabilitation in a practical manner and that the bridge superstructure spans had to be replaced entirely in order to extend the service life of that bridge.

This, we believe, is the case as well at the Champlain Bridge in the case of Section 5 and Section 7. In the context of an extension of the bridge service life to 50 years or more, it is likely that the entire superstructure for Sections 5 and 7 would have to be replaced.

There are methods by which this could be accomplished while at the same time minimizing interference with vehicular traffic.

If it were desired to replace the spans in Sections 5 and 7 in this manner, it is envisaged that a combination of methods would be required to effect such major construction works. These might include:

- The use of heavy lift equipment to lift and transport complete spans including both the existing spans and new spans. This technology has been used many times and has recently been introduced to Canada. It should be noted, however, that these are very large heavy spans and the equipment required to move them in this way would be substantial and costly, and may need water depths which cannot be achieved/guaranteed everywhere under the bridge.

- Sliding of both the existing spans and new spans laterally into position during possessions of the crossing. This technique has been used in Canada to slide bridge structures weighing as much as 3000 tonnes laterally into position. Currently four such sliding bridges are under construction in Toronto. A considerable amount of temporary works is necessary to enable such construction including the temporary works necessary to support the new span in its temporary position adjacent to the bridge and the temporary works necessary to support the old span in its final position prior to demolition. There are a number of examples of similar bridge construction in Europe, one of which is the replacement of the Quaibrucke in Zurich over the River Limat, a project which involved the simultaneous sliding of an existing five-span bridge and a new five-span bridge in such a manner as to replace the existing bridge by the new bridge over a weekend including dealing with electric trams. Typical bridge slides can be accomplished at the rate of about 2.5m per hour using double-acting hydraulic jacks controlled by a computerized system.

- The use of floating equipment where water depths permit to lift out the existing spans and to float in and lift down into position the new spans.

All of these methodologies have proven feasible on other projects and economical where circumstances warrant, particularly where traffic is to be maintained to the maximum extent possible. In the case of the Champlain Bridge however, it is likely that the requirements for the maintenance of traffic are so significant that even these methods might prove to be difficult if not impossible to install in the windows of time which would be made available. There is always the risk, too, that something goes wrong in the midst of one of these operations when the entire crossing is out of service because a span is not in its final position.

A possible methodology for dealing with the deteriorating condition of the pier caps in Sections 5 and 7, which have been exposed to water from leaking expansion joints, would be to reduce the cantilevers by adding steel or reinforced concrete below the cantilevers. However, these methodologies add load to the bridge foundations. The post-tensioning which is being used in lieu of the reduction in the cantilever length for improving the capacity of the bridge, may not be appropriate in the long term given the condition of the concrete and the inability which has been reported to remove all of the deteriorated concrete prior to implementing the post-tensioning across the tops of the pier caps.

It seems likely to us that despite the theoretical possibility of carrying out such construction works on Sections 5 and 7 which could result in the construction of relatively light-weight structural steel girder spans rather than the current relatively heavy prestressed concrete girder spans, and hence a reduction of the seismic loads on the bridge, the temporary works associated with such construction are so extensive, and the risks of something going wrong on any one of the 50 replacement spans significant enough, that these methods, while technically possible, would not be preferred in the context of the overall 50-span structure comprising Sections 5 and 7. They would take a very long time, cost very considerable amounts of money, and entail some risk of interference with traffic which was unplanned. This is particularly the case as they would require, in addition to the replacement of the superstructure, significant prior works to be carried out on the foundations, pier stems and pier caps, including possible modification of the pier caps to reduce the cantilevers and extensive works to enable the rehabilitation of the substructure to be compatible with a 50-year design life (if this is even possible given the condition of the concrete in these structures).

In this regard, it is worth noting the evidence as to possible alkali aggregate reaction. Tests have been carried out on the concrete materials on the bridge to determine whether or not alkali aggregate reaction is affecting the bridge. Our understanding of the test results was that these were inconclusive although it appeared that there was some potential for alkali aggregate reaction to take place with consequent expansion and degradation of the concrete. In addition, tests have been carried out on the concrete in the bridge which suggests that the concrete was not adequately air-entrained in accordance with modern practice and therefore its general resistance to the effects of freeze/thaw cycles is not adequate.

At issue in effect is the basic quality of the concrete in the bridge, something which the test results as to alkali aggregate reaction and entrained air (which relates to the durability of the concrete under freeze/thaw cycles) together with the observations as to the very severe deterioration which is taking place on the substructures of the bridge and the exterior girders of the superstructures, suggest to us is in question. This is another significant factor in suggesting that it is very difficult, if not impossible, for the replacement of many significant elements of the bridge, to rehabilitate the bridge to serve over the next 50 years with appropriate levels of safety and durability.

4. RISK MANAGEMENT

Studies have been carried out with regard to the analysis of risks associated with prestressed concrete spans of the type found in Sections 5 and 7 of the Champlain Bridge. These were carried out in 2007 and 2008. These studies included description of the structure, a report on the general condition of the bridge element-by-element, report on investigations such as measures of the precompression in the concrete girders and measures of the concrete compressive strength, studies of the load-carrying capacity of the bridge, study of the loss of cables, studies of chloride ion penetration into the concrete, study of a range of rehabilitation methodologies, comments with regard to the degree of knowledge of the condition of the various elements of the bridge ranging from 'well-understood' to 'unknown', and comments with regard to some key uncertainties. It was noted, for example, that structural calculations may not take complete account of the state of degradation of the concrete and that the amount of precompression as a result of the prestressing in the cables, remained uncertain at the time the report was written. In essence, a certain amount of judgment is required in assessing the parameters applied to the bridge in terms of the risk which it poses, given its condition and particularly given the unknowns which cannot altogether be defined despite the best efforts of technology to do so.

We suggest that a better understanding of the condition of the 50 spans which are in question in Sections 5 and 7 might be gained by removing two of them from the bridge (using a rapid replacement technology on say two spans, one at either end of the bridge) and then carefully and methodically testing and perhaps disassembling them to some degree. This would be an interesting exercise in learning much more about the condition of the bridge in detail, but it does have the disadvantage of taking a considerable amount of time, of incurring some risks in the removal of the spans from the bridge and their replacement using rapid replacement techniques, by new spans which could remain permanently in service, and by the fact that even testing 2 out of 50 spans may be indicative but not definitive as to the condition and nature of deterioration of the remaining 48 spans. It would, however, be one method for further quantifying the risks associated with this superstructure type (integrated prestressed concrete girders and deck).

The risk analysis carried out in 2008 reports in further detail with regard to the actual identification of risks, the relative seriousness, and their effects should they, in fact, be realized. Examples included shear failure of a girder and shear failure of a pier cap. Many other possible risks were identified, the causes documented, and a commentary as to the impact of the risk, should it be realized, was noted.

A few risks identified were the corrosion of reinforcing and prestressing steel on the bridge and the effect which this has on the concrete of the bridge, and the uncertainties with regard to the actual state of the various components of the bridge and therefore uncertainties as to the actual capacity of the various elements of the bridge to carry load under critical conditions. It is noted in the risk analysis, for example, that given the transverse post-tensioning in the bridge deck, the consequences of the failure of a girder are difficult to determine in precise fashion. (Although it has been noted elsewhere that the failure of a girder may cause the loss of a span, this cannot be altogether certain.)

Essentially the risk management work which we have reviewed suggests that there are some failure mechanisms which could be quite sudden (those involving shear failure, for example) and that the effects of such failures on the overall structure cannot altogether be predicted.

5. LIFE CYCLE COSTING

Life cycle costing analyses have been carried out including a study in 2006. Typically and very simplistically, life cycle costing analyses generally conclude that the longer that a major expenditure (such as the construction of a new bridge to replace an existing bridge) is postponed, the lower is the life cycle cost. However, in the case of the above-noted 2006 study, it is noted that to maintain the existing bridge in service for the next 50 years, is just as costly as to maintain the existing bridge in service for the next 15 years and to construct a new bridge in 2020. This result is explained and can be expected because the Champlain Bridge in its current condition requires a great deal of investment to maintain it safely in service year-by-year, and to maintain it safely in service for the next 50 years is extremely costly. In addition, maintaining the existing bridge in service for the next 50 years entails carrying much larger risks than are associated with the construction of a new bridge and the maintaining of the new bridge in service for the next 50 years, for example.

The life cycle costing analysis work which has been done is another indicator that maintaining the existing bridge in service in the longer term is not appropriate and entails costs which have the potential to exceed the costs of constructing a new bridge in the near future (on a life cycle costing basis). Rehabilitation also carries greater uncertainty as to costs, as issues associated with rehabilitation of an existing bridge under traffic are more significantly variable than the issues associated with constructing a new bridge away from traffic, and the maintaining of the existing bridge in service entails inevitably the carrying of much more risk than is entailed in the construction of a new bridge, vis-à-vis public safety and security.

6. DESIGN-BUILD DELIVERY METHOD USED

Sections 5 and 7 of the Champlain Bridge were constructed not in accordance with the original design for the bridge but in accordance with the contractor's alternative which was the least expensive of some 28 submissions received. The process of accepting the contractor's alternative resulted in a low initial capital cost. It also resulted in a structure which has failed to perform satisfactorily in service for an appropriate period of time and which, for a range of reasons, is virtually incapable of being repaired in such a manner as to enable it to continue in service with an appropriate level of safety and a reasonable level of risk, beyond more than perhaps a few years, and then only in conjunction with a very substantial costly programme of rehabilitation which, in and of itself, cannot reduce the risks to levels which would be appropriate to the typical bridge of this age. Our experience is that this inherent disadvantage of design-build projects is being repeated again now on some current design-build projects. This can be controlled to some extent by careful documentation and vigilance on the part of the Owner and the Owner's engineering team.

7. UNCERTAINTIES

As has been pointed out in several of the reports produced as to the condition, structural analysis, definition of rehabilitation schemes and risk analysis studies, as well as physical examination of the bridge, there is some uncertainty with regard to the condition of the bridge and its ability to carry loads, as this pertains to Sections 5 and 7 in particular. In part, this is the result of the observable damage, for example, to the prestressing wires and tendons in the prestressed concrete girders, and similar uncertainties with regard to the condition of the transverse post-tensioning which secures the girder flanges to the deck infill sections. The condition of the concrete in the superstructure of Sections 5 and 7 is variable, ranging from very high compressive strengths in the order of 70 MPa, to concrete which has deteriorated and completely fallen away from the bridge. The behaviour of the bridge superstructure spans in Sections 5 and 7 is also somewhat in doubt as to how and if an individual span would continue to carry load successfully, even its own self-weight, in the event of the loss of one of the edge girders, the edge girders being the key concern as it is these girders that are in the poorest condition of any element of the bridge superstructures. The loss or collapse of an edge girder would imply significant damage to, perhaps loss of, the transverse prestressed tendons which are anchored to these edge girders, with results that are not easily predictable. This uncertainty is compounded by uncertainties as to the effect of the transverse prestress in the diaphragms which also would be adversely affected by the loss of such a girder. In conjunction with the poor condition of many of the edge girders in Sections 5 and 7, these girders unfortunately carry truck loads which cannot be diverted away from the edges of the bridge (as this would pose safety issues to the bus traffic using the bridge, we understand). The configuration of the superstructure spans in Sections 5 and 7 constitutes now a fatal flaw in the bridge in that restoring these superstructure spans (of which there are a total of 50) to an appropriate level of safety and reliability, requires their replacement by new superstructures. At the same time, there are serious concerns with the condition of the pier caps, pier stems and the foundations which support these superstructures, and these elements require very significant works in order to make them compatible with current requirements, particularly as to seismic load-carrying capacity, durability, and safety. The condition of the concrete in these structures is such that it may not be appropriate or possible to attempt to modify these structures to essentially meet modern standards while, at the same time, continuing to carry traffic loads on the bridge.

8. ENVIRONMENTAL ASSESSMENT

The original bridge began to be considered in 1955 and was open to service in 1962, a period of about 7 years. Construction projects of this magnitude now tend to take much longer. This is largely because of the Environmental Assessment process. Because of the condition of the Champlain Bridge, the risks which are being run as it remains in service even as it is being rehabilitated, and the duration of time which the rehabilitation scheme entails, it may be appropriate to seek ways and means of dealing with the environmental assessment requirements in some fashion parallel to proceeding with the design scheme which is appropriate for the creation of an integrated structure with an expected lifetime of at least 75 years.

9. POSSIBLE HYBRID SCHEMES

While we have considered and can envisage methodologies for dealing with all of the issues associated with the deficiencies found in Sections 5 and 7, as well as the more limited deficiencies which exist in Section 6, the requirement that such works be carried out while still maintaining the bridge in service to vehicular traffic is so constraining that it is anticipated that such construction would take an inordinately long time and that the cost of such work would be high compared with a new bridge which is of the same length as the approach Sections 5 and 7. There is in the main span, however, a considerable amount of structural steel which represents a significant investment for Canada, and which includes a relatively new orthotropic steel deck which has improved the performance, safety, load-carrying capacity, and durability of that main span. The piers supporting the main span are currently being repaired. If the piers can be repaired to a level to be compatible with an additional 50 year life, for example, it seems likely that the structural steel can survive in service for 50 years as well, and that this core component of the bridge might, if an appropriate scheme were found which would satisfy the functional requirements of the crossing for the next 50 years, continue to serve for a period to time approaching or even exceeding 50 years with an appropriate continuing maintenance repair and rehabilitation programme. This could only be considered if the current six-lane configuration of the bridge is considered appropriate for the long term. One way which this might be accomplished while at the same time eliminating Sections 5 and 7, and at the same time maintaining the crossing in service with minimal interruption to vehicular traffic during construction, would be to build new Sections 5 and 7 by means of twin three-lane structures upstream and downstream of the existing Sections 5 and 7 and connecting them with an appropriate alignment to the main span. It may be worth studying this alternative as, if it is geometrically possible, the monies already invested in the main span would continue to serve for a long period of time and could be compatible, in terms of safety and durability, with a new bridge, provided that the issue of seismic loading can be dealt with in such a manner to ensure that the bridge from end-to-end meets the current requirements for a lifeline bridge.

If such a scheme can reasonably be conceived in the context of maintaining traffic on the bridge to the appropriate level of service throughout construction, consideration could also be given to schemes which utilize the rehabilitated new and existing hybrid Champlain Bridge thus created, to carry vehicular traffic, while transit is carried on a separate new structure.

10. NEW CROSSING

A simpler solution is, of course, to build a complete new structure and demolish the existing Champlain Bridge, creating a new structure which meets all current requirements from structural and functional perspectives, and which carries vehicular and transit loading as required.

11. LOAD RATING OF THE CHAMPLAIN BRIDGE

A considerable amount of work has been carried out over a period of years with regard to load rating this bridge. This work was carried out with a view to identifying and defining the actual capacity of the bridge elements compared to the requirements set out in the Canadian Highway Bridge Design Code.

Relevant reports include the following:

- Report by Buckland & Taylor Ltd. on the "Evaluation of King Post Option for Section 5 Girders" dated 19 October 2007. This report focused on the shear carrying capacity of the prestressed concrete girders in Section 5 of the Champlain Bridge. Results from that analysis showed that the utilization factor for shear in the girders is very close to 1.0 if it is considered that all of the prestressing strands are fully effective. In fact, as reported elsewhere, all of the prestressing strands are not fully effective and, as Buckland & Taylor Ltd. note, some unknown amount of post-tensioning loss has occurred in these girders. It is possible, therefore, that the reserve capacity, compared to the Canadian Highway Bridge Design Code requirements, in shear in some of these girders is very close to zero or perhaps less than zero in some cases. It is to be noted that Buckland & Taylor Ltd. retained somewhat conservative values of the longitudinal strain at mid-height of the girders. Alternate assumptions or measures to reduce this longitudinal strain can have significant impacts on the utilisation factor.

- Dessau Soprin Consulting Engineers reported in July 2007 as to the load carrying capacity of the bridge in their "Étude de la capacité portante et émission de permis spéciaux (2001-2002)". This work was carried out in the context of the Canadian Highway Bridge Design Code in force at that time. This report suggested that in accordance with the results of their evaluation, the bridge was adequate to carry normal traffic. However, special attention was directed at the interior girders in Sections 5 and 7A where the utilization factor is as high as 1.03, that is again very close to unity. This suggests again that, without modification and given that there may be some deterioration of these girders, the reserve capacity in the girders is very low and may approach zero.

- While not directly associated with load rating, Buckland & Taylor Ltd.'s Report on the Updated Fatigue Life Evaluation of the Champlain Bridge Orthotropic Deck Panels dated April 28, 2006 comments upon the safe and mean fatigue lives expected for the main span and approach spans steel deck panels. They conclude that there is a 5% probability that fatigue damage will start after 11 years and 8 years respectively in the main span and approach span's steel orthotropic decks, and that mean fatigue lives of 76 years and 62 years respectively are expected for the main span and approaches decks. As may be expected given the complex nature of this behaviour, there is some uncertainty as to how long such decks will last in service on this bridge accordingly.

- SNC Lavalin produced a report entitled "Sections 5 et 7 Effet de vent sur les piles". This was a report dated June 2010. This report concludes that taking into account all factors, it is reasonable to conclude that the piers in Sections 5 and 7 are capable of resisting the effects of wind.

- Tecsult Inc. produced a report entitled "Etude de la capacité font portante des piles de la Section 6 par rapport aux forces de vent". This report was dated July 2009. The conclusion was that some of the piers supporting Section 6 of the bridge have insufficient load carrying capacity compared to the requirements of the Canadian Highway Bridge Design Code given the condition of the piers at that time, and given the combination of various loads including wind. They recommended that significant repair works be carried out to these piers in order to permit the utilization factor to be improved to be in the order of 1; that is, to be improved to the condition whereby the loads on and resistance of these structures were approximately equal.

In summary, a reading of these reports suggests that the theoretical load carrying capacity of the bridge compared to the requirements of the recent editions of the Canadian Highway Bridge Design Code is, in some cases, marginal, depending heavily upon the assumptions made, the condition of the various elements, and repairs which have been, or are being, carried out.

12. CONCLUSIONS

- The Champlain Bridge is a major crossing of the St. Lawrence River between Montreal and the South Shore. Completed in 1962, it carries heavy vehicular, truck and bus traffic and is a critical link in Montreal's transportation system.

- The Champlain Bridge is designated as a lifeline bridge. This has implications as to its required behaviour under seismic loading. The current bridge is not compatible with a lifeline designation.

- It is understood that the bridge is functionally deficient in respect of current traffic and transit demands as well as traffic and transit demands expected in the medium and long term.

- The bridge segment under study here comprises three sections, namely the main span section (Section 6) which crosses the St. Lawrence Seaway by means of a structural steel bridge section, and two prestressed concrete approach sections (Sections 5 and 7) comprising 50 spans in total.

- The structural steel superstructures (Section 6) are in relatively good condition. While these structures provide some structural redundancy, they are not considered to have a large excess of live-load carrying capacity. The orthotropic steel deck on the main structure has however improved the live-load carrying capacity as well as its rigidity and durability.

- The reinforced concrete substructures supporting the structural steel superstructures are considered to be in fair condition. Extensive repair works are being carried out on these substructures. These repairs do not, however, include seismic rehabilitation or retrofit.

- The main span, Section 6, structures have not been originally designed for seismic loads corresponding to current seismic requirements for a lifeline bridge.

- The approach spans, Sections 5 and 7, comprise prestressed concrete girders integrated by means of transverse post-tensioning with deck infill sections between the girder flanges and with diaphragms between the girders, the entire assembly comprising an orthogonally-stressed grillage of concrete. This superstructure scheme was the least expensive of some 28 alternatives to the original design. These alternatives were proposed by contractors and the least costly one was accepted for implementation. In conjunction with this superstructure scheme, a compatible substructure system comprising pier caps, pier stems, and circular foundations founded on bedrock, was also developed for construction.

- The approach spans were not designed for seismic loading corresponding to current seismic loading requirements for a lifeline bridge.

- Analyses have shown that the capacity of the bridge to carry wind loading is marginal.

- The bridge was not designed to be resistant to corrosion and/or concrete degradation which would be caused by salting of the bridge. In the initial years of its service, we understand it was not salted but soon thereafter salting of the bridge commenced. In consequence, the bridge has now suffered some significant deterioration of the concrete and steel which comprise the bridge, particularly on the bridge approaches where both the superstructure and the substructures have been adversely affected.

- The bridge has been the subject of a methodical inspection, investigation, testing, analysis, repair and rehabilitation programme under the auspices of The Jacques Cartier and Champlain Bridges Incorporated. This programme continues in place and currently is programmed for 10 years at a cost of some $212 Million with the continuing necessary inspections, investigations, testing, analyses, repairs and rehabilitation required to manage the risks associated with maintaining the bridge safely in service during that time frame. In this context, works are currently underway on the bridge including rehabilitation of pier caps, for example, augmenting the works carried out on other elements of the bridge including strengthening of the edge girders of the approach spans by means of the addition of external post-tensioning. We understand that this external post-tensioning programme may be expanded to include all of the edge girders on the bridge, a total of 100 such girders, in the context of a 10-year programme and on a priority basis depending upon the condition of the girders.

- As is common with the type of deterioration which is observed in the edge girders and in many other elements of the bridge, it can be expected that deterioration will progress at an increased rate which is characterized by an exponential curve, as time goes by.

- Because all of the rehabilitation works which would be necessary to rehabilitate the bridge cannot be carried out instantaneously, there are and will continue to be risks associated with the operation of this bridge. These risks are being managed in the context of a methodical programme and have been carefully studied by The Jacques Cartier and Champlain Bridges Incorporated. Nevertheless, the risks cannot altogether be quantified and some unknowns are associated with them. For example, because the actual condition of the post-tensioning steel in the prestressed girders cannot altogether be quantified and there is evidence of broken wires and broken tendons in some of these girders, some unknown risks are associated with these elements.

- Analyses have suggested that the loss of an edge girder in the approach spans could result in the progressive collapse of the span.

- The repairs and the restoration of load-carrying capacity being incorporated in the edge girders are considered to be appropriate given the condition of the girders and given the virtual impossibility of replacing the girders as a result of their highly-integrated construction with the diaphragms, with the deck infill panels, and with adjacent girders, to all of which they are connected by high-strength prestressing steel. The addition of external post-tensioning is considered to be an economical methodology for adding to the load-carrying capability of the bridge edge girders on the approach spans, and to reducing risks over the relatively short term. Such post-tensioning is not considered compatible with long term service as it is exposed to the elements and is attached to the structure of the girders in a way which is not equivalent to new construction inasmuch as, in part, the attachments must be made to girders which have themselves already suffered some deterioration.

- Life cycle costing studies have shown that the cost of maintaining the bridge in service in the order of 15 years, that is, the relatively short term, and then replacing it with a new bridge is virtually the same as the cost of maintaining the existing bridge in service for some 50 years. This is an unusual finding in the context of a bridge in reasonable condition and it suggests that this bridge is in very much poorer condition than would be typical for bridges of its age and importance. It suggests also that the costs of maintaining this bridge in service will be very large while, at the same time, risks associated with maintaining the bridge in service cannot altogether be eliminated and will almost certainly be greater than the risks associated with a new bridge.

Our impression of this bridge is that it has many deficiencies, some of which are very significant and that its continued operation in service, even in the context of the methodical and organized inspection, testing, analysis, rehabilitation and repair programme which is underway, entails some risks which cannot altogether be quantified.

The deficiencies and associated risks are such that the Champlain Bridge should be replaced by a new crossing and an expedited process to accomplish this should be implemented as soon as possible.

In the meantime, the current rehabilitation programme should continue.