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Seismic Evaluation and Retrofit Study of the Jacques Cartier Bridge in Montreal

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ABSTRACT

The Jacques Cartier Bridge (the Bridge) was built between 1925 and 1930 prior to the development of modern seismic design standards. This 3.4 km-long bridge is an urban landmark and an essential link of the transportation network in the greater Montreal area and consists of approaches, and main spans over the St. Lawrence River between the cities of Longueil and Montreal, in Québec. It is divided into nine sections of separate structural types and is principally comprised of under-deck steel trusses on lightly reinforced or unreinforced massive concrete piers, or on steel towers on the North approach. Section 3 and Section 7 are exceptions with over-deck steel trusses to accommodate longer span lengths and increase navigation clearance over the St. Lawrence River. Section 5 includes the Île Sainte-Hélène Pavilion (ISHP), which serves as a bridge deck, and its two access ramps.

The Jacques Cartier and Champlain Bridges Incorporated (JCCBI) is considering extending the service life of the Bridge beyond its 150th anniversary (2080). Seismic risk mitigation is an important part of this upkeep program for service life extension. An initial seismic study was completed in 2017-2019. This paper presents a follow-up study which captures the recent significant seismic hazard increase in Montreal from the 5th to the 6th generation model determined by the Geological Survey of Canada (GSC) as well as the proposed conceptual seismic retrofit designs for three intervention levels ranging from preventing significant structural damage to limited access under the 2475-year design earthquake.

The principal challenges and the retrofit strategies developed to address them are presented in this article. In particular, the most robust strategy involves replacement of existing bearings with seismic isolation bearings, and the use of concrete jacketing with foundation enlargement or installation of rock anchors for the concrete piers. Seismic isolation of the concrete deck from the steel trusses is achieved through yielding of the existing steel restrainers for some sections, and installation of dampers is proposed to prevent deck pounding onto the trusses. Other studied retrofit techniques include the installation of shear keys, new pile foundation system connected to the existing foundations, allowing rocking response, or providing new shear walls in the ISHP. The most robust strategy with seismic isolation, aiming at an essentially elastic behavior and the least post-earthquake damages, is recommended based on a cost/benefit analysis.

Keywords: Seismic evaluation, Seismic retrofit, Historic bridge, Seismic isolation, Asset management

INTRODUCTION

The resilience of critical infrastructure plays an important role in Canada's economy. In general terms, all the processes, systems, technologies, facilities and services essential to the health, safety, security and economy which are related to different sectors such as transportation, energy, information or other can be classified as critical infrastructure. One of the vital infrastructure in the city of Montreal, which can be classified as a critical infrastructure, is the Jacques Cartier Bridge which links the island of Montreal to the South Shore in Longueuil. Any malfunction in this type of infrastructure could have adverse effects, notably on the economy and the population in general. Thus, such critical infrastructure should stay functional after a major seismic event to provide safe food, reliable energy, and other essential services to the public [1].

According to the National Strategy on critical infrastructure, in the case of an emergency, the owners and operators are the first response authorities. Therefore, the seismic performance of the Jacques Cartier Bridge has been evaluated in order to prepare for a major seismic event [1]. Seismic retrofit scenarios are considered in conjunction with their financial feasibility. In addition, the ability of bridge owners to react after a natural disaster can increase the resilience of a critical infrastructure. A post-earthquake intervention plan is prepared to ensure a quick post-earthquake response.

JACQUES CARTIER BRIDGE

Background

At the time the Jacques Cartier Bridge was designed, there was no consideration for resistance to earthquake forces. Basically, the first concept of seismic design was incorporated into the 1966 version of the CSA specification for highway bridges. Seismic studies of the Jacques Cartier Bridge and earthquake preparedness plan were completed in the late 1980s early 1990s, that is over 30 years ago. Significant advance has been made to the standard seismic design approach and for seismic evaluation and rehabilitation of existing and non-standard bridge configurations [2][3]. One of the major changes is the determination of the seismic performance objectives by the Bridge's owner, in collaboration with engineers. More recently, JCCBI looked at other seismic performance studies of existing bridges in order to better understand the context and conducted the first seismic performance study on the Jacques Cartier Bridge [1][4][5].

General description

The Jacques Cartier Bridge is a five-lane structure that is 3.4 km long in total, including its approaches and the iconic steel cantilever through-truss main spans over the St. Lawrence River (Figure 1). The Bridge connects the cities of Montreal and Longueuil. It crosses the Seaway channel, Île Notre-Dame and Île Sainte-Hélène, providing access and an exit ramp to Île Sainte-Hélène. The passage on the Bridge is evaluated at approximately 35.8 million vehicles per year. It is located between the Victoria Bridge and Louis H. Lafontaine Tunnel, which both connect the island of Montreal to the South Shore.

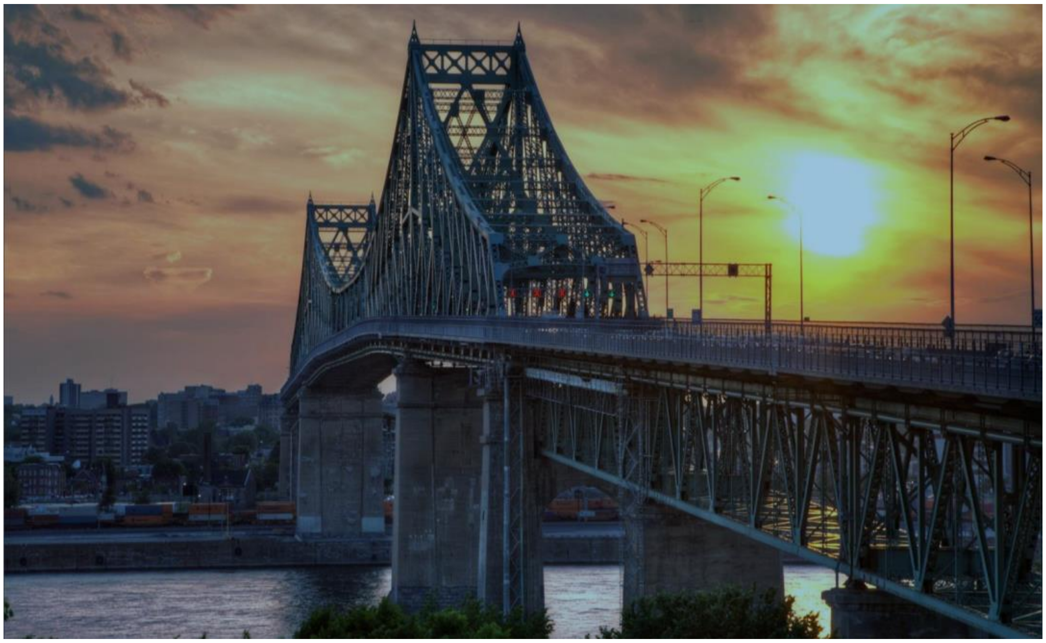


Figure 1. Main span (Section 7) of the Jacques Cartier Bridge (view from South/Section 6)

At the present time, the roadway width is 18.3 m between the barriers, and a cantilevered sidewalk as well as multipurpose path are located on the downstream and upstream side of the Bridge respectively. The superstructure is supported on 61 axes as presented in Figure 2. Sections 2 to 6 constitute the South approach (Longueuil side) between axis 0 and 23 and include the ISHP (Section 5). This pavilion is a four-storey building with concrete walls and steel columns. The concrete roof acts as a deck for the Bridge. Section 7 is the steel cantilever through-truss main spans (a total length of 590.4 m) over the St. Lawrence River. Sections 8 and 9 constitute the North approach (Montreal side) between axis 26 and 61. The plan view of the Bridge is shown in Figure 3.

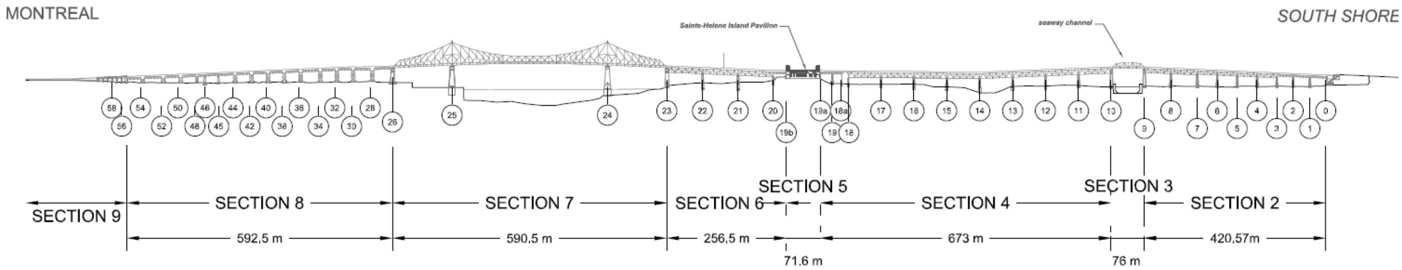


Figure 2. Spans upstream elevation of Jacques Cartier Bridge – Sections 2 to 9

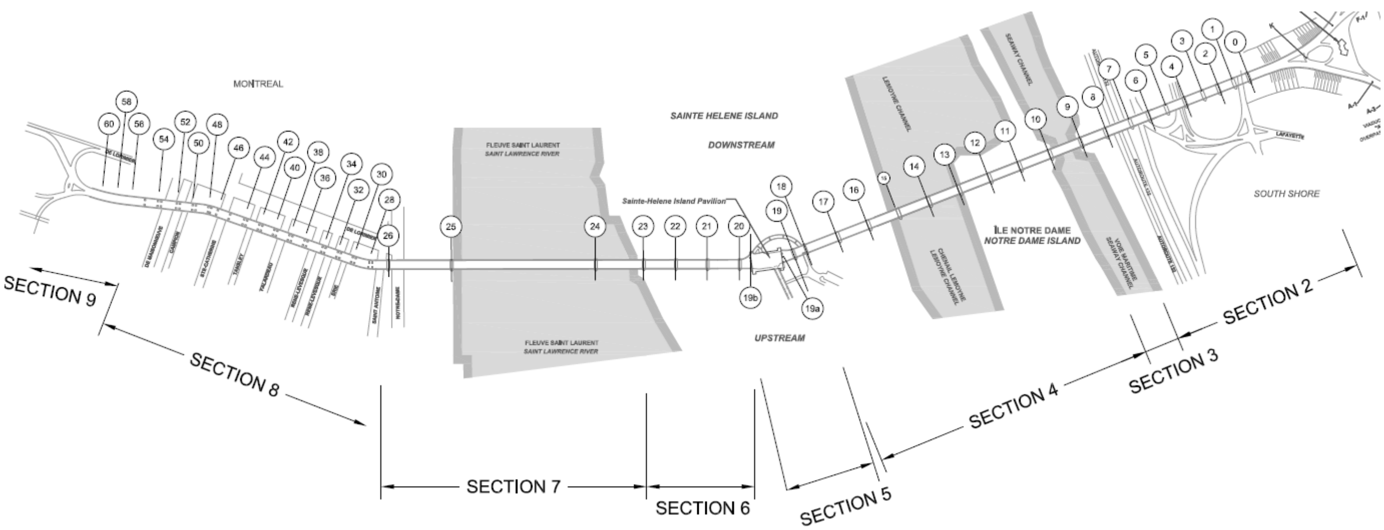


Figure 3. Plan view of Jacques Cartier Bridge - Sections 2 to 9

Several modifications and rehabilitations have occurred over the years. Different repair and reinforcement projects are in progress to maintain the Bridge's safety. Two major repairs of the Bridge during its life included enhancement of the Bridge and the deck replacement.

SEISMIC PERFORMANCE LEVEL DEFINITION

Defining the targeted seismic performance level is an important part of seismic retrofit process for a structure. The cost of retrofit and repair work depends on the performance level selected. A performance objective is based on two principal criteria which are damage limitation and the level of service that the bridge can provide after an earthquake.

Damage after a major seismic event should be limited to ensure stability of the structure as a minimum, and potential reparability of the structure. Defining a performance level for an existing historic lifeline bridge is an important and complex task that involves several stakeholders. While its definition should consider and integrate all the needs previously listed in terms of public security and services, preparing a plan aiming to inspect the structure and restore its function for emergency vehicles and general traffic use would reduce the socio-economic impact in case of post-earthquake damages to this vital transportation link. Thereby, it is important to develop a process to define the balance between the investment in retrofit work and the acceptable residual damage. Consequently, three levels of seismic retrofit have been defined in order to better assess the benefits, impacts and risks associated with each retrofit scenario. Moreover, this approach will help the owner of the infrastructure decide on the most practical seismic retrofit plan [1][4].

First level of seismic retrofit: This first level of seismic retrofit aims for public safety (“life safety”). In case of an earthquake, the Bridge would be severely damaged but still standing. The users would at least be able to evacuate the Bridge on foot. For this level of seismic retrofit, the Bridge would undergo damage leading to probable replacement for the 2475 years return period and experience important damages for the 975 years return period.

Second level of seismic retrofit: The second level of seismic retrofit aims to guarantee a minimum level of service that ensures the immediate passage of emergency vehicles and partial recovery for public circulation within weeks. The Bridge would undergo important damages for the 2475 years return period and would experience repairable damages for the 975 years.

Third level of seismic retrofit: The third level of seismic retrofit aims to reduce the potential damage of the Bridge in order to ensure a higher level of service. This level would allow immediate passage of the emergency vehicles and partial recovery for public circulation within days. Consequently, in the third level, the Bridge would have damages that are repairable for the 2475 years return period and would have minor damages for the 975 years return period.

For each of the three seismic retrofit levels, the extent of the retrofit work to be performed on the existing Bridge would be associated with an extent of expected residual damages and the acceptance of a corresponding level of risk. The goal is to achieve a satisfying balance between seismic retrofit costs and reduction of risks/residual damage repair costs, as illustrated in Figure 4. Moreover, a post-seismic action plan needs to be prepared with respect to the acceptable residual damage for the selected retrofit work strategy.

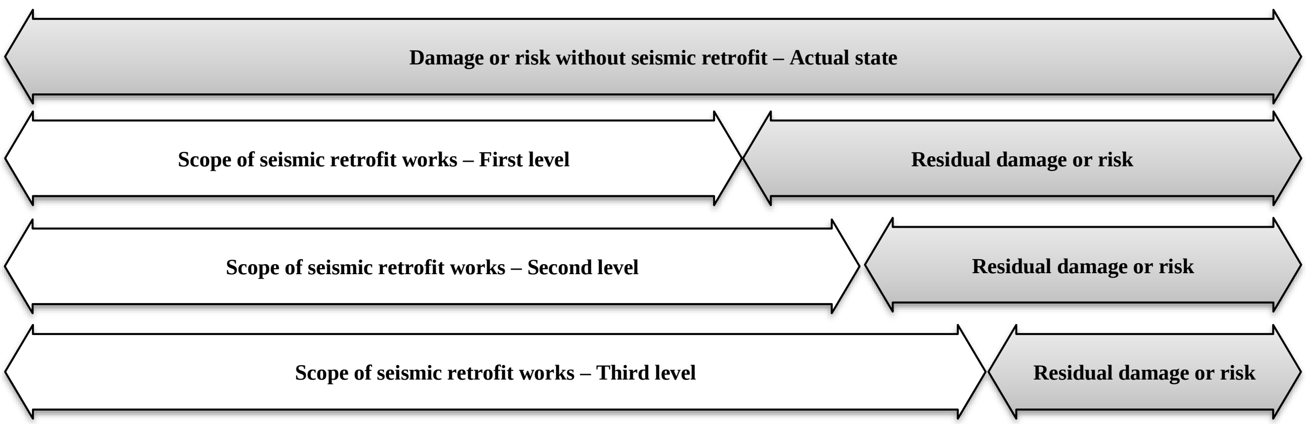


Figure 4. Balance between extent of retrofit work and risks or residual damage

CONCEPTUAL SEISMIC RETROFIT DESIGNS

Basis for the complementary study

An initial seismic performance evaluation of the Bridge was completed in 2017-2019[1][5], based on the 5th generation seismic hazard developed for National Building Code of Canada (NBCC) 2015 and the performance levels and objectives defined in the Canadian Highway Bridge Design Code (CAN/CSA-S6-14)[2][6]. The most critical issues that were identified pertained to the bearings and substructure levels.

The 6th Generation hazard model of Canada was recently developed for the 2020 NBCC. This recent update to the seismic hazard model by Geological Survey of Canada has led to about 40% increases in the seismic hazard values in the Montreal area[6][7][8][9].

The seismic performance evaluation of the Jacques Cartier Bridge was revisited to assess the effect of these recent updates to the seismic hazard on the bridge elements deficiencies. In addition, different scenarios of conceptual seismic retrofit schemes were developed to address the identified deficiencies corresponding to three intervention levels targeting three levels of performance from preventing significant structural damage to limited access under the 2475-year design earthquake.

South Approach (Longueuil side)

The South approach is characterized by the massive concrete piers which are built on masonry blocks filled with lean concrete at the base, with water break detail at the base (taper) and topped with an unreinforced concrete section (Figure 5). Most of the piers are supported directly on bedrock (site class A or B), with the exception of some piers that are founded on a series of timber piles embedded in overburden soil (site class C) and have been rehabilitated with the addition of a partial height concrete jacket.

Figure 5. General view of section 2 of the Bridge (South approach)

Replacing the truss bearings with seismic isolators would reduce the demands on the superstructure elements, including on the deck bearings and on the truss members, and is expected to completely eliminate the need for reinforcement work on the steel members. Replacing the truss bearings with seismic isolators would allow an elongation of the vibration period, as well as a uniform distribution of the lateral forces in the isolators rather than a concentration in the fixed bearings according to the configuration of the existing articulations.

Seismic isolation of the superstructure does not eliminate seismic deficiencies of the concrete piers due to significant pier self-inertial responses. Due to the size of the piers, a ductile behavior would not be achievable. The most practical retrofit solution would consist in concrete jacketing of the concrete piers with a reinforced concrete jacket, extending the service life of the piers at the same time, and aiming at an essentially elastic behavior. The details of the retrofit solution would have to be tailored to adjust to the characteristics of each pier (such as varying pier heights, previous concrete jacketing or presence of masonry on a portion of the height). To minimize large excavations and rehabilitation work on the lower sections of the piers, a prestressed rock anchor solution is also proposed.

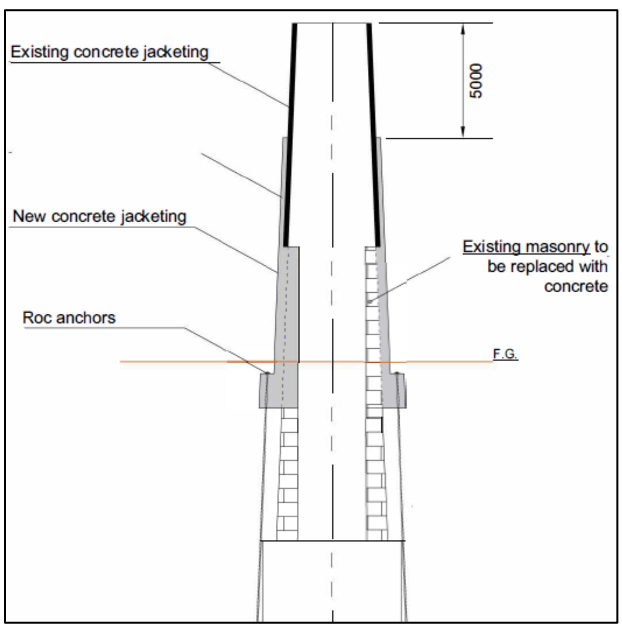


Figure 6. Example of proposed retrofit concept for the piers

Elevated section over the Seaway channel

To increase the navigational clearance during the construction of the St. Lawrence Seaway channel, the typical under-deck truss superstructure between axis 9 and 10 was replaced by an over-deck truss type in the 1950s (Figure 7). As a result, the bearings' elevations were raised with the construction of lightly reinforced pedestals, as shown in Figure 9 8, which have been retrofitted with a 150 mm thick reinforced concrete jacket in 2011.

Figure 7. General view of Section 3 of the Bridge

While the strengthening of the deck stoppers is not recommended, as it could otherwise lead to overloading of the steel floor system (stringers and floor beams), dampers should be installed between the concrete deck and the steel floor system to dissipate seismic energy, significantly reduce relative displacements and prevent pounding of the concrete deck against the over-deck truss members after failure of the deck stoppers during a major earthquake event.

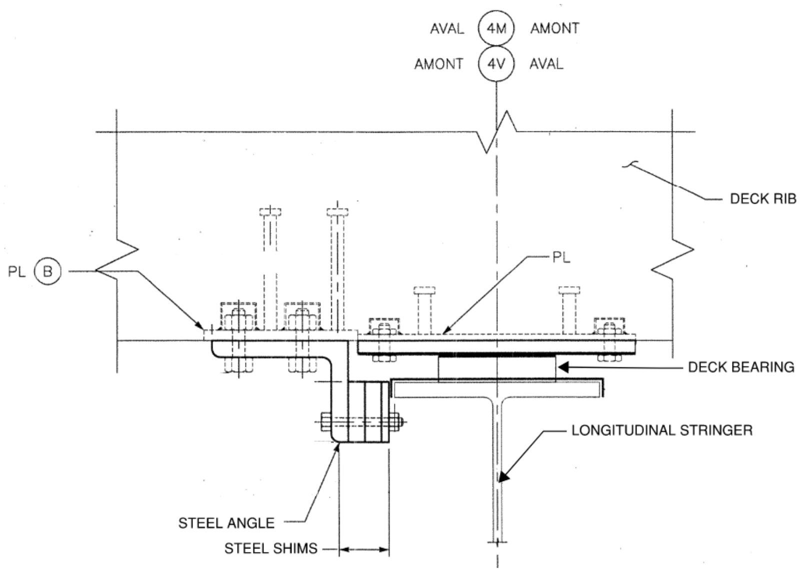


Figure 8. Lateral restrain of the deck panels

Replacement of the existing bearings, either the original spherical bearings or the *lubrite* bearings, with seismic isolation bearings would be very effective in reducing the seismic demands in the superstructure and eliminate strengthening work on the superstructure elements. However, like the rest of the South approach spans, concrete jacketing of the concrete piers, including the pedestals, would still be required to increase the piers' capacity (Figure 9).

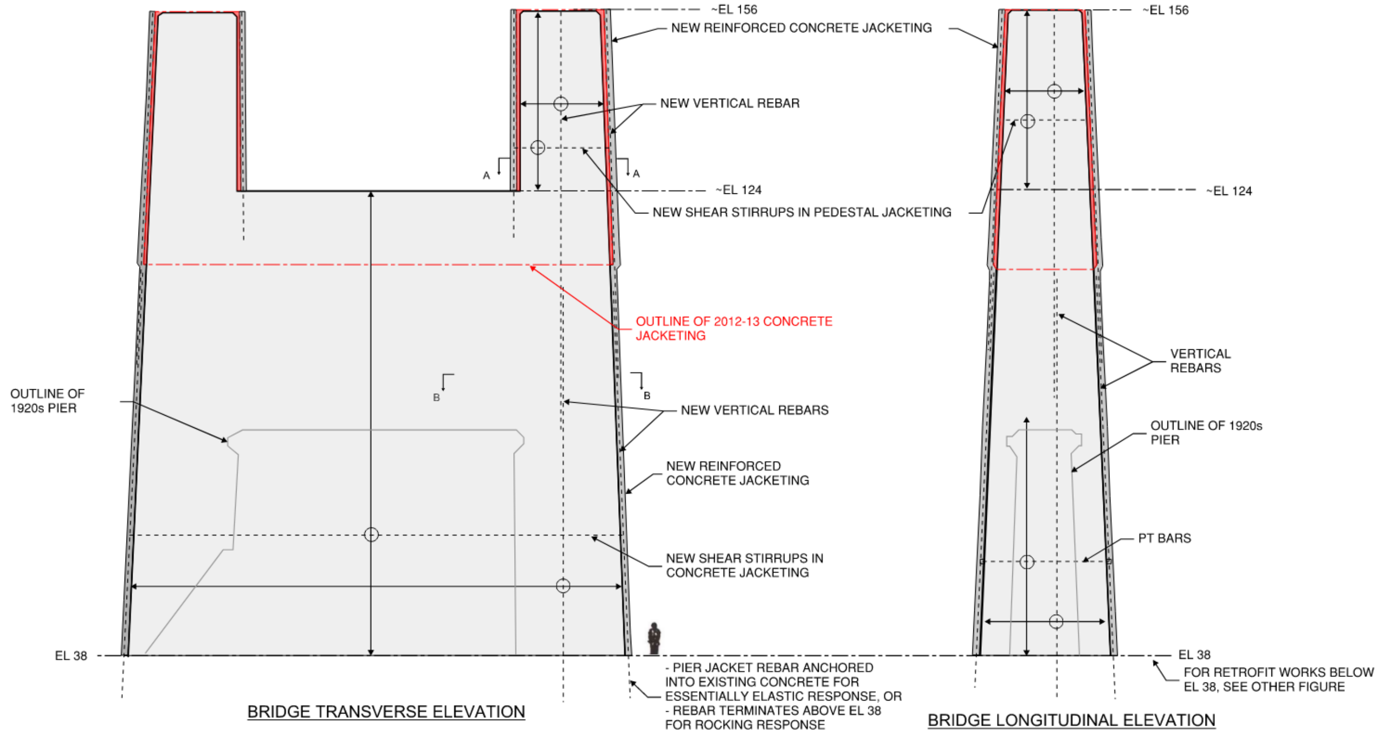


Figure 9. Concrete jacketing of the enlarged and raised elevated piers

In addition, during the construction of the seaway, the foundations of piers were altered to excavate a channel and build walls on each side, along the face of the piers' foundations. Foundation enlargement should be completed as part of retrofit scenarios for at least the second and third levels of retrofit. Another approach could be to allow rocking response at the base of the pier and save significant underground work, although the level of post-earthquake service would be more limited. Figure 10 illustrates the two retrofit options.

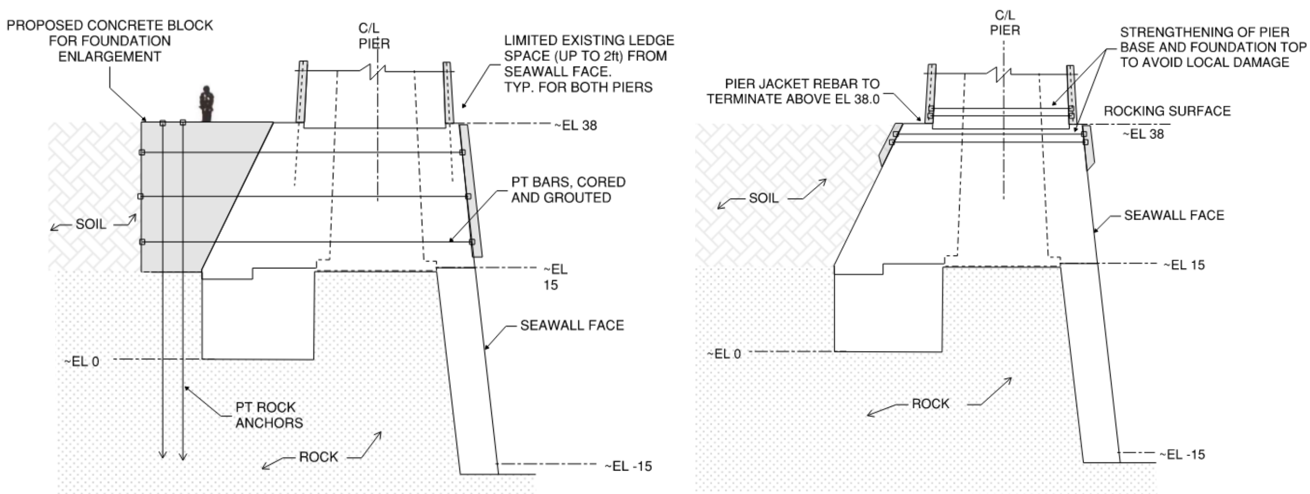
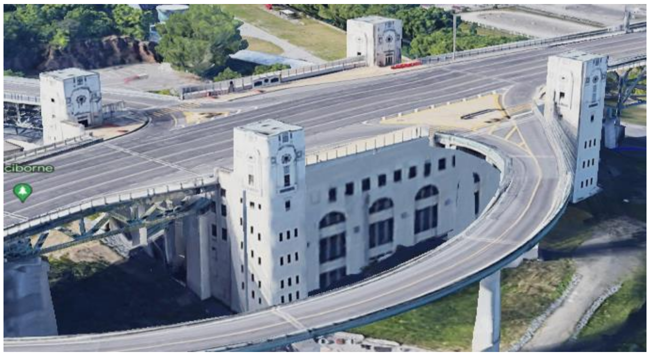


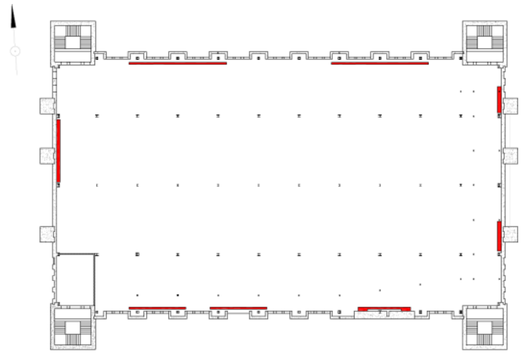
Figure 10. Two (2) of retrofit concepts for the foundation system (a) Foundation enlargement for essentially elastic response; (b) Local strengthening at base of pier allowing rocking response

Île Sainte-Hélène Pavilion

The existing reinforced concrete perimeter walls of the Pavilion support their own weight. The weight of the roof (Bridge deck), that of the floor as well as that of the vehicles on the roof are supported by the steel framework composed of columns and steel beams. Maintaining the structural integrity of the steel frame during seismic response is essential (Figure 11).



(a)



(b)

Figure 11. Ile Sainte-Helene Pavilion (a) Global view from Google Earth; (b) Location of proposed shear walls

The seismic rehabilitation strategy consists of adding new shear walls in the longitudinal and transverse directions and located close to the peripheral walls. To allow natural light and to marry the new walls with the original architecture of the building, the new walls would have openings similar to the existing ones. The new walls, combined with the existing walls, would limit seismic horizontal displacement demands to maintain the structural integrity of the steel frame supporting the gravity loads. The seismic rehabilitation design assumes that some cracking will develop in existing and new reinforced concrete walls under the 2,475-year design earthquake but the extent of cracking will be limited by designing the new walls to remain essentially elastic for the 2475-year design earthquake. However, to ensure a robust behavior, the new walls should be detailed for a ductile behavior corresponding to R = 3.5 in agreement with the NBCC.

Main Span

The main span of the Bridge (Figure 1) is also supported on massive concrete piers. The anchor piers, founded on rock and soil~~,~~ are arch-shaped piers. The arch parts support “wind shoes”, which are steel elements transferring the lateral forces from the superstructure to the substructure. The main piers, founded on rock, are wall-type piers supporting the “main shoes” into which the truss chords, main diagonals and portal posts connect. All four piers of the main span would require the installation of reinforced concrete jacketing, and the anchor piers require deepening of the arch-shape pier cap. Footing enlargement would also be required at those anchor pier locations for at least the second and third levels of retrofit (Figure 12).

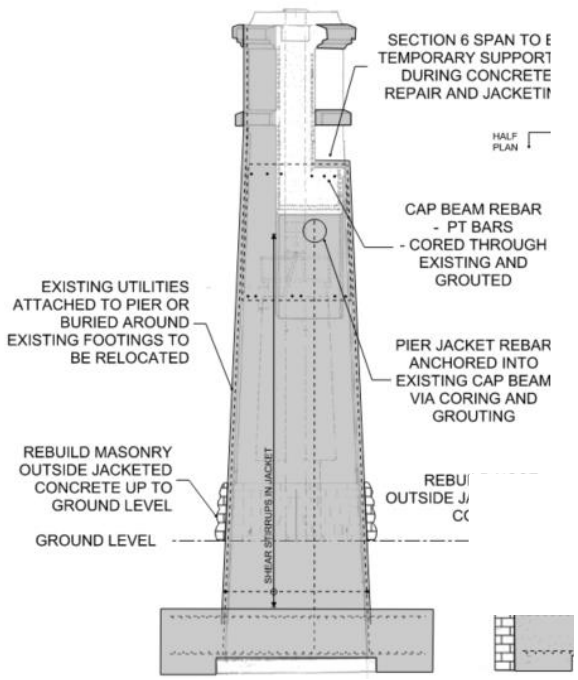


Figure 12. Proposed retrofit concept of the arch-shape anchor piers

An alternative retrofit solution, leading to a lower performance level, would be to allow a rocking response for the anchor piers.. The tie-down articulations are expected to allow a rocking response at the base of the pier without compromising the structural integrity of the superstructure. Accepting such movement of the anchor piers would save significant underground work. However, the level of post-earthquake service would be significantly impacted. Finally, unlike the approach sections, the Section 7 substructure cannot be isolated from its superstructure due to the tie-down connections. As such, localized steel strengthening work would be required along the length of the truss spans for selected truss members, plan bracing members and connection elements, such as at end of the suspended span as illustrated in Figure 13.

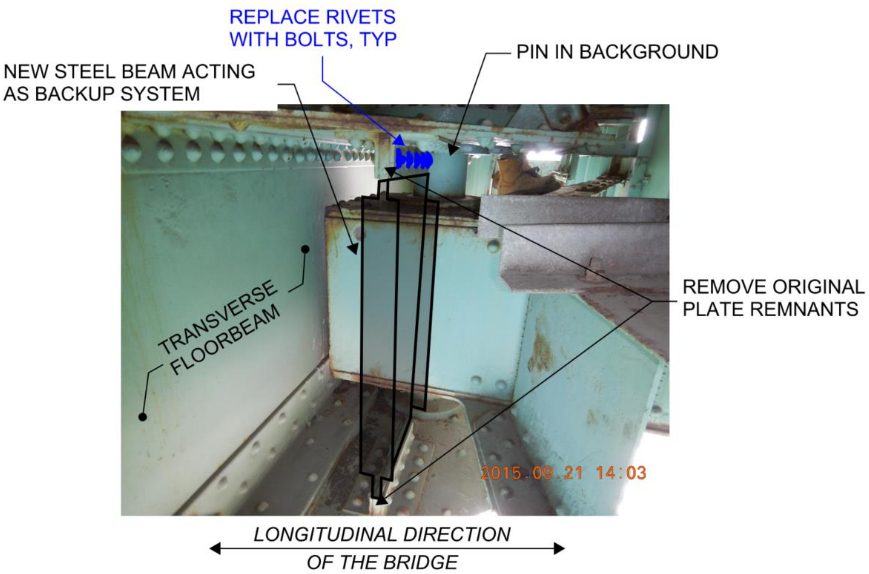


Figure 13. Seismic retrofit concept of the transverse restraint at end of suspended span

Like the elevated section of the Bridge over the Seaway channel, the deck of the main span is comprised of precast deck panels with transverse ribs spanning over the longitudinal stringers and is supported on a series of deformable bearings or sliding bearings with the addition of lateral stoppers for the bearings on the stringer lines on either side of the deck centerline. The stoppers are not designed to resist the seismic loads and are expected to act as a fuse during a large earthquake. As a result, the deck steel flooring system would not be overloaded. However, dampers would be required to be installed between the concrete deck and the steel floor system to significantly reduce relative displacements

North Approach (Montreal side)

The North approach superstructure is similar to the one in the South approach but is supported on steel towers founded on pedestals for most of its length, as illustrated in Figure 14.

Figure 14. General view of Section 8 of the Bridge

The preferred retrofit solution for the North approach is like the one for the South approach: use of seismic isolation bearings. Seismic isolators would reduce the demands on the existing deck bearings on the steel floor system. The use of the seismic isolation as seismic retrofit would also minimize the need for steel truss member strengthening as only end diaphragms would remain deficient.

In addition, seismic isolation would also be effective in reducing seismic loads for the steel towers, eliminating the need for their retrofit.

CONCLUSION

Since the Jacques Cartier Bridge is a critical infrastructure in the Montreal area, its seismic performance during a major earthquake would have significant impact on the population and on the economy. This study performed on the Bridge confirms that a retrofit is possible. This study helped JBCCI develop and analyze different scenarios, compare the costs associated with each scenario and define three retrofit levels. These results will be valuable for decision making and for choosing a retrofit strategy.

Considering the characteristics of the Jacques Cartier Bridge, superstructure seismic isolation combined with concrete pier retrofit would be the preferred retrofit strategy for the approach spans as it achieves a higher and more robust seismic performance (Retrofit of Level 3: emergency vehicles can use the Bridge and partial recovery for public circulation is possible) at only marginally higher costs as compared to other intervention levels (e.g. allowing rocking responses). This retrofit strategy would significantly reduce the potential impact on public traffic and minimize repair and reconstruction cost in the event of a major earthquake. Further investigation would be required, however, to confirm the preferred retrofit scenario.

ACKNOWLEDGMENTS

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