Performance based Seismic Evaluation of the Jacques-Cartier Bridge Part 1: Owner's perspective

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ABSTRACT

A jewel of our heritage, the Jacques Cartier Bridge is an icon of the Montreal region and has been a fixture of the city's skyline since 1930. It is an essential link and ensures the integrity of the transportation network in the greater Montreal area. The Jacques Cartier Bridge was designed in the late 1920s at which time there were no seismic standards in effect for bridges. In terms of traffic circulation, it is a key link between the island of Montreal and the Monteregie area. In being so, it had become a priority for The Jacques Cartier and Champlain Bridges Incorporated (JCCBI, the Corporation) to further analyze the risks a seismic event would represent for safety and durability of the structure.

Seismic activity in the province of Quebec has proven necessary to take into consideration seismic effects in designing new bridges as well as for evaluating and retrofitting existing structures.

Considering its high heritage character, social and economic value, Jacques Cartier Bridge's unique and complex structure is a precious Canadian asset. According to the definition in CSA S6 Canadian Highway Bridge Design Code [1], it should be classified as a lifeline bridge.

In 2016, a mandate was awarded to the Parsons-Cima+ consortium to conduct an analysis and evaluation of the seismic performance of the bridge. The mandate also included the achievement of geotechnical investigations, a soil and foundation survey and a detailed assessment of the behavior of bearings. Subsequently to the analysis of the seismic performance, mandate also included the preparation of a preliminary design study of seismic retrofit of the bridge in accordance with the requirements of the Canadian Highway Bridge Design Code CSA S6-14 [1], considering three level of performances in terms of expected damage and service.

The examination of seismic issues related to the protection of this important structure is fully in line with the JCCBI approach to sound asset management and lifespan prolongation of this invaluable bridge. The results of the analysis will allow the Corporation to evaluate the capacity of the Jacques Cartier Bridge foundations, define the level of seismic performance and as well as evaluate the risks and costs related to a potential seismic retrofit works.

The seismic performance evaluation of the Jacques Cartier Bridge revealed important issues and technical challenges for JCCBI, particularly in terms of the definition of the performance criteria and the level of service to be provided for an existing lifeline category bridge. For this purpose, a committee was created to support JCCBI's engineers and is composed of three internationally renowned structural experts. This committee was given the mandate to accompany the Corporation through technical issues and provide support to analyze strategic choices and directions. Contractual documents focused mainly on the requirements relating to the seismic evaluation methodology and the concept of risk management according to three levels of seismic performance.

Keywords: Performance criteria, seismic risk, performance based approach, existing bridge evaluation, seismic retrofit.

INTRODUCTION

The resilience of critical infrastructure plays an important role in Canada's economy. One of the vital infrastructures in Montreal city is the Jacques Cartier bridge which links the Montreal island to the south shore at the Monteregie Area. Thus, it should stay functional after a major seismic event in order to provide safe food, reliable energy, and other essential services to the public. The ability of bridge owners to react after a natural disaster can increase the resilience of a critical infrastructure [2].

In general terms, all the processes, systems, technologies, facilities and services essential to the health, safety, security and economy which are related to the different sector such as transportation, energy, information or others can be classified as critical infrastructure. If there is any malfunction in this type of infrastructure, signification harm to public confidence, adverse economic effects or catastrophic loss of life can be occurred [3]. In addition, according to the National Strategy on critical infrastructure, in the case of an emergency, the owners and operators are the first response authorities [3]. Therefore, the Jacques Cartier bridge can be classified as a critical infrastructure and it is important to evaluate its seismic performance in order to act accordingly after a major natural disaster such a seismic event.

Considering the importance of the Jacques Cartier bridge and the fact that the behavior of earthquakes is very complex and unpredictable, the JCCBI has decided to perform a seismic performance analysis to find out the related risks to the bridge in case of a major seismic event. Furthermore, a progressive seismic retrofit program will be established with the focus in reducing the risk of bridge collapse, increasing the seismic resistance of the Jacques Cartier bridge and minimizing the loss of life as well as the injury after an earthquake.

JACQUES CARTIER BRIDGE

Background

At the time when 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 [4]. Therefore, in 1989 the JCCBI mandated the H.H.L. Pratley consultant to perform a study on the seismic behavior of the Jacques Cartier bridge. The study was performed using accelerations parallel to the bridge centerlines. The results showed that a manual for the inspection procedures after an earthquake should be prepared for the entire bridge because of the fact that it was not designed to resist horizontal forces caused by earth [5].

Accordingly, in 1990 an earthquake preparedness plan for the Jacques Cartier bridge was prepared in four parts [6].

- Determining the level of damage expected from an earthquake;
- Identification of instrumentation required to perform the different types of measurement;
- Description of the bridge inspections corresponding to the preparedness plan;
- Recommendations for instrumentation methods.

However, seismic studies performed on the Jacques Cartier bridge [5-6] were performed more than 30 years ago. One of the significant advances has been the requirement of a performance based approach for non-standard bridge configurations, a requirement that has only been introduced in the latest version of CSA S6 Canadian Highway Bridge Design Code. One of the consequences of this requirement is the determination of the seismic performance objectives by the owner, in collaboration with the engineers. Furthermore, JCCBI looked at other seismic performance studies of existing bridges in order to better understand the context [7-8-9].

Structural description

The Jacques Cartier Bridge is a five-lane steel cantilever truss structure that is 3.4 km long including approaches. The bridge spans the St. Lawrence River between the cities of Montreal and Longueuil. It crosses the Seaway channel, Notre Dame island and St. Helen's island providing access and an exit ramp to St. Helen's Island. 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.

The first idea of building the Jacques Cartier bridge was created in 1874, but it was not open until 1930 because of lack of financing. According to the first design, the centerline was supposed to be dedicated to the tramway. But in 1956, the centerline was opened to the traffic as well.

At the present time, the width of the deck is 22.1m having two cantilevered paths for cyclists and pedestrians. The roadway wide is 18.3m between the curbs. The piers built of concrete, steel or masonry are located on 61 axes as presented in Figure 1. In Section 8, other than two piers in masonry, the rest of the piers are made of steel towers and installed over the concrete pedestals. The riveted steel trusses are positioned over the piers and support the load of the concrete deck. In addition, Section 7 is a steel truss cantilevered superstructure located between Montreal island and Saint Hélène's island within axes 23 and 26.

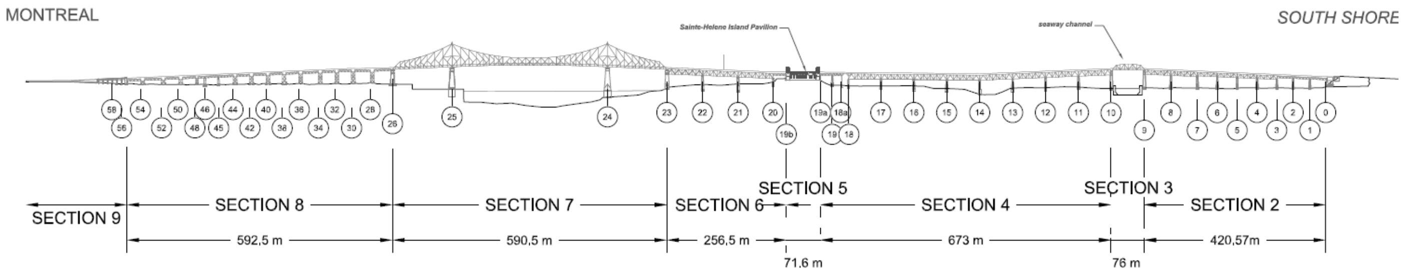

Figure 1. Spans upstream elevation of Jacques Cartier Bridge – Sections 1 to 8

Furthermore, a building supports the bridge at Section 5 located at St. Helen's island. This building named St. Helen's island pavilion is a four-storey building with concrete walls and steel columns. The concrete slab of the structure at the roof level acts as a deck diaphragm for the bridge. During the seismic performance evaluation, this particularity was considered in order to comply with the requirement of the national building code of Canada (NBCC) [10] as well as CSA-S6-14 [1] provision. The plan view of the bridge showing the position of the access ramps and the St. Helen's island pavilion is presented in Figure 2.

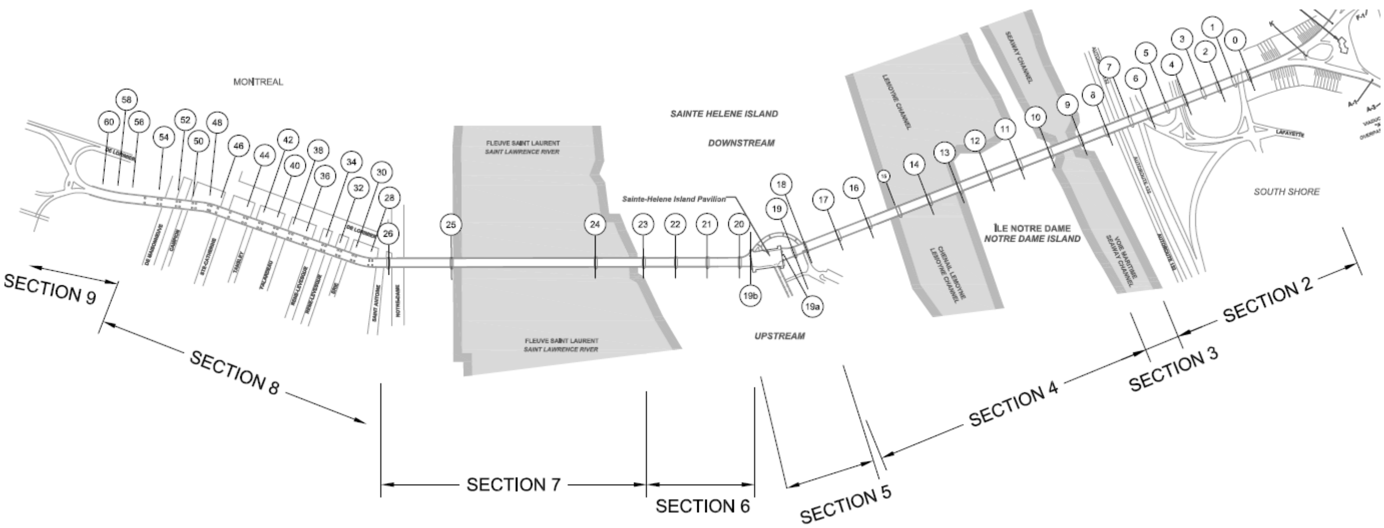

Figure 2. Plan view of Jacques Cartier Bridge - Section 1 to 8

Important rehabilitation work

The Jacques Cartier bridge had several interventions during its life so far. Different repair and reinforcement projects are in progress to ensure the safety of the public who uses this important transportation link on a daily basis. Two major repairs of the bridge during its life are presented in this section.

RAISING OF THE BRIDGE

To accommodate the St. Lawrence Seaway, truss spans were raised and piers were extended in 1955. The entire operation was performed with no traffic interruption. The bridge deck located at Section 3 above the St. Lawrence Seaway channel between piers 9 and 10 was jacked up and a new span was erected. Other piers were extended in length from 12.2m to 36.5 meters depending on their position. The final pier configurations are unusual and have an impact on the seismic performance evaluation.

DECK REPLACEMENT OF THE BRIDGE

All five lanes of the Jacques Cartier bridge on the entire length were subjected to deck replacement between 2001 and 2002. The new prefabricated deck was built of the prestressed and post-tensioned panel of high-performance concrete. The replacement work was done without any disruption of the traffic during the rush hour. The increased weight of the deck on the bridge has limited impact on the seismic performance evaluation. The entire deck of the bridge, across its full length and width, was replaced between 2001 and 2002. Contrary to the jacking up the bridge, these modifications may have less impact on the seismic performance evaluation.

SEISMIC PERFORMANCE EVALUATION

A consortium formed by Parsons-Cima+ was awarded the seismic performance evaluation of the bridge. In addition, geotechnical investigations, a soil and foundation survey and detailed assessment of bearings were part of the mandate. In addition, the preparation of a preliminary retrofit study was requested in accordance with the Canadian Highway Bridge Design Code CSA S6-14 [1], considering three levels of seismic retrofit scenarios. Given the importance and the traffic volume of the Jacques Cartier bridge, it is classified as a lifeline bridge.

Preliminary results of the seismic performance evaluation revealed that some of the bridge structural elements have unsatisfying performance under seismic loads, specifically, masonry columns, some of the foundations, some of the principal truss beams and some of the bracings [11].

Table 1- Summary of performance evaluation based on consultant's results

Sections	**Return period**		
	475 years	975 years	2475 years
Sections 2, 4 and 6			
Piers (some)	RD	RD	ID
Extended parts of piers of axis 0 to 13	RD	RD	RD
Foundations of piers 1 to 14	RD	RD	ID
Piles of piers 15 to 16	ID	ID	ID
Section 3 (Over the seaway)			
Bracing of the deck (some)	RD	RD	RD
Lateral bracing (some)	ID	ID	ID
Bearings and restrainers	RD	RD	RD
Section 5 (pavilion)			
Building envelope	RD	RD	RD
Deck's diaphragm	MD	MD	RD
Section 5: Ramp at upstream side			
Fixed bearings	MD	MD	ID
Piers H0 and H2	ID	ID	ID
Pier H1	MD	MD	ID
Section 7			
Piers	RD	ID	ID
Bearings	MD	ID	ID
Truss beams and bracings (some)	MD	MD	ID
Section 8			
Piers	ID	ID	ID
Pedestals (some)	RD	RD	ID (all the axis)
Moveable bearing	ID	ID	ID
Bracings	RD	RD	RD

MD: Minor Damage **RD**: Repairable Damage **ID**: Important Damage

Seismic performance level definition

Defining the target seismic performance level is an important part of seismic retrofit process for a structure. The cost of retrofit and repair work will be defined directly according to the selected target seismic performance level.

A performance objective is based on two principal criteria which are damage limitation and protection of the structure. However, the protection of the structure is related to the level of service to ensure after an earthquake.

In the case of a lifeline bridge, the damage after a major seismic event should be limited to ensure the safety of the public, stability and the reparability of the structure. Furthermore, the acceptable damage level should be defined in order to minimize the impact on the traffic during repair works. It should be noted that according to Clause 4.11.4 of CSA-S6-14 [1], for an existing bridge the definition of the appropriate performance criteria is the responsibility of the bridge owner.

Nonetheless, defining a service level for a lifeline bridge is an important and complex task that should involve several stakeholders. It should also consider and integrate all the needs in terms of public security by preparing a plan aiming to protect the structure and reduce the socio-economic impact in case of any loss of a vital transportation link such as the Jacques Cartier bridge.

Thereby, it is crucial to prepare a collaborative plan with other transport entities as part of the National strategy for critical infrastructure program [3]. In addition, it is important to develop a process to define the limit between the investment and the acceptable residual damage. Moreover, a post-seismic action plan needs to be prepared with respect to the acceptable residual damage as shown in Figure 3.

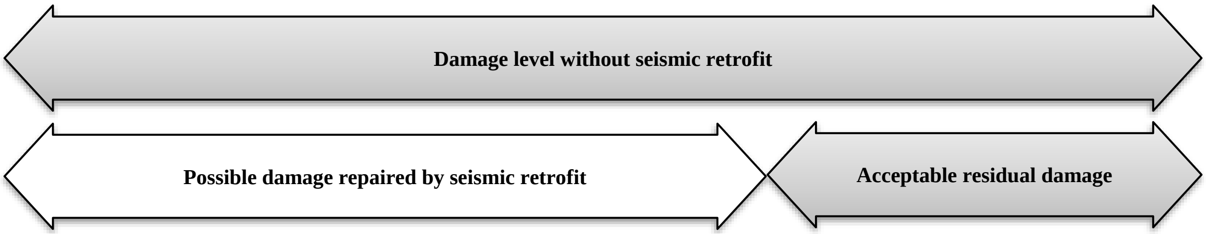

Figure 3. Summary of seismic retrofit strategy

Basically, residual and acceptable damage should not have a significant impact on bridge serviceability. Likewise, it should be possible to repair the bridge temporarily without complete closure of the traffic lanes and in a relatively short time. As an example, the damage of the deck joints can be considered an acceptable residual damage.

Proposed seismic performance criteria

In order to define the target performance level for each seismic retrofit level, the result of seismic performance evaluation for each of the three return periods is considered. The basic concept of seismic performance based approach for new bridges stated in CSA-S6-14 [1] is shown in Figure 4.

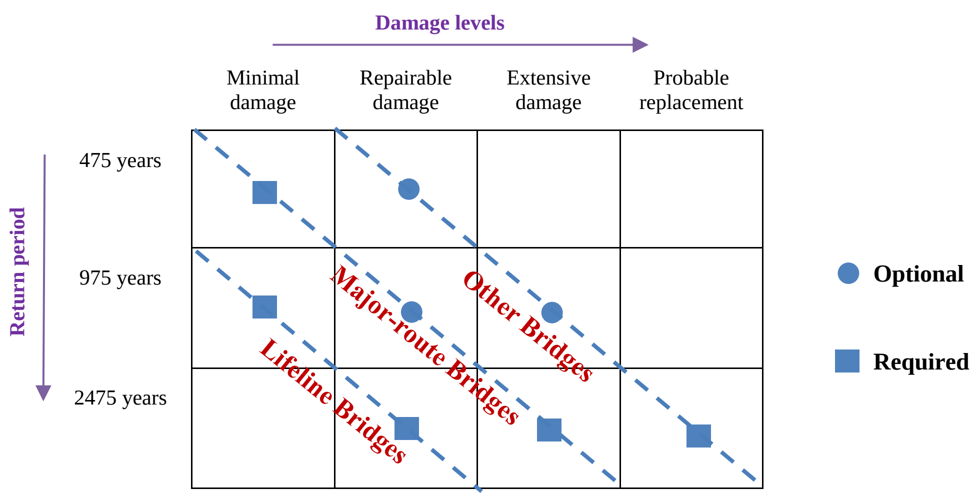

Figure 4. Bridge damage levels for different return periods according to CSA-S6-14

The results obtained from the seismic performance evaluation of the Jacques-Cartier bridge show that the behavior in two first return period is very similar and the major part of the important elements such as piers are consistently in the repairable or the important damages category. These results confirm that for an existing bridge, it is neither realistic nor relevant to expect no damage after a seismic event for a return period of 1/475. Consequently, for seismic retrofit of the Jacques-Cartier bridge, it was deemed appropriate to consider only the return periods of 975 years and 2475 years.

SEISMIC RETROFIT APPROACH DRIVEN BY PIERS

Seismic performance analysis of the Jacques Cartier bridge reveals that the piers are the most challenging elements and they most probably will guide the seismic retrofit. Therefore, all piers are considered in the present approach [12].

The results demonstrate that for the 975 years return period, most piers (majority) would have repairable damages and some of them (minority) would experience probable loss. The same exercise for the 2475 years return period shows that most piers (majority) would have a probable loss and some of them (minority) would have repairable damages (Figure 5). However, according to CSA-S6-14 [1], for the design of a new lifeline bridge, the damages should be minor for the 975 years return period and should be repairable for the 2475 years return period earthquake.

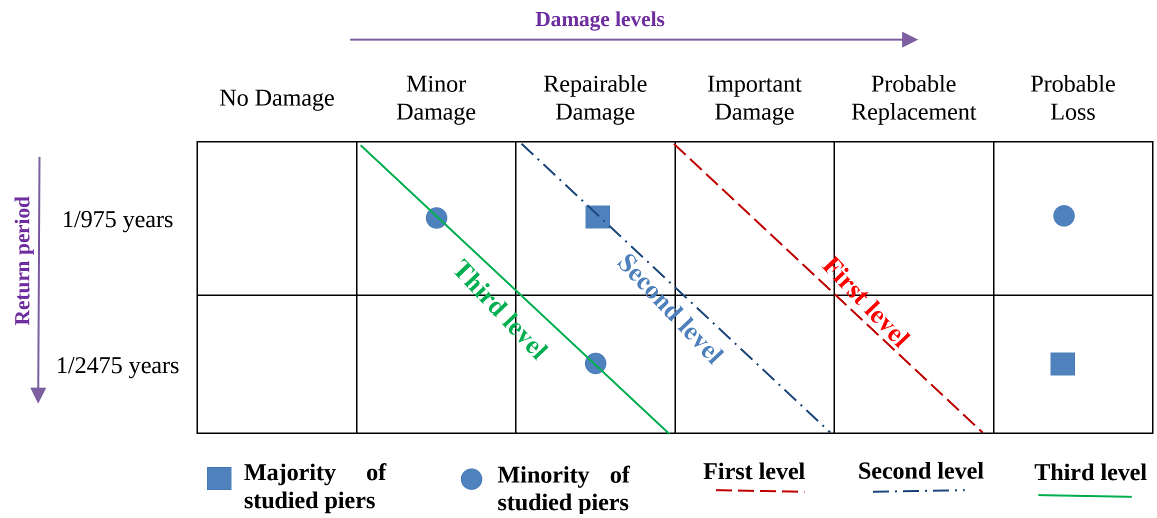

Figure 5. Piers Seismic performance according to the engineer's evaluation

Consequently, three levels of seismic retrofit are considered (Figure 5) in order to better analyze the impact of each retrofit level. Moreover, this approach will help the owner decide on the most realistic seismic retrofit plan [12].

First level of seismic retrofit: This first level of seismic retrofit aims for public safety (no loss of life). In case of an earthquake the bridge would be severly damaged but still standing. The users would at least be able to evacuate the bridge on foot. In this level of seismic retrofit, the piers 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 level of minimum service that ensures an immediate and secure passage of the emergency vehicles and partial recovery for public circulation within weeks. The piers 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 aims to reduce the potential damage of the bridge in order to ensure a higher level of service. This level would allow an immediate and secure passage of the emergency vehicles and partial recovery for public circulation within days. Consequently, in the third level, the piers would have damages that are repairable in the 2475 years return period and would have minor damages in the 975 years return period.

PERFORMANCE OBJECTIVES UNDER CONSIDERATION FOR THE JACQUES CARTIER BRIDGE

In light of the evaluated behaviour of piers, three seismic retrofit scenarios are being considered for the Jacques Cartier bridge too keep the owner assess the feasability of each [12].

Immediate service: The potential damage of the structure should be limited in order to ensure the secure and immediate circulation for emergency vehicle as well as the recovery for the public service in a few hours. The repair works should not cause any service interruption.

Limited service: The bridge should be operational and repairable without any closure for emergency vehicles. At least 50% of the traffic lanes should be operational in a few hours after the earthquake. The regular service should be recovered in 2 to 4 months.

Interrupted service: The bridge should be serviceable for emergency vehicles and restrained circulation should be possible after an inspection. It should be repairable but complete closure may be needed for repairs.

Furthermore, an iterative process should be followed to confirm understanding of the retrofit investment compared with the time and the recommended budget for repair after an earthquake. It should be noted that four damage levels (Minor damage, Repairable damage, Important damage and Probable replacement) presented in Figure 6 have the same definition as presented in the CSA/S6-14 [1].

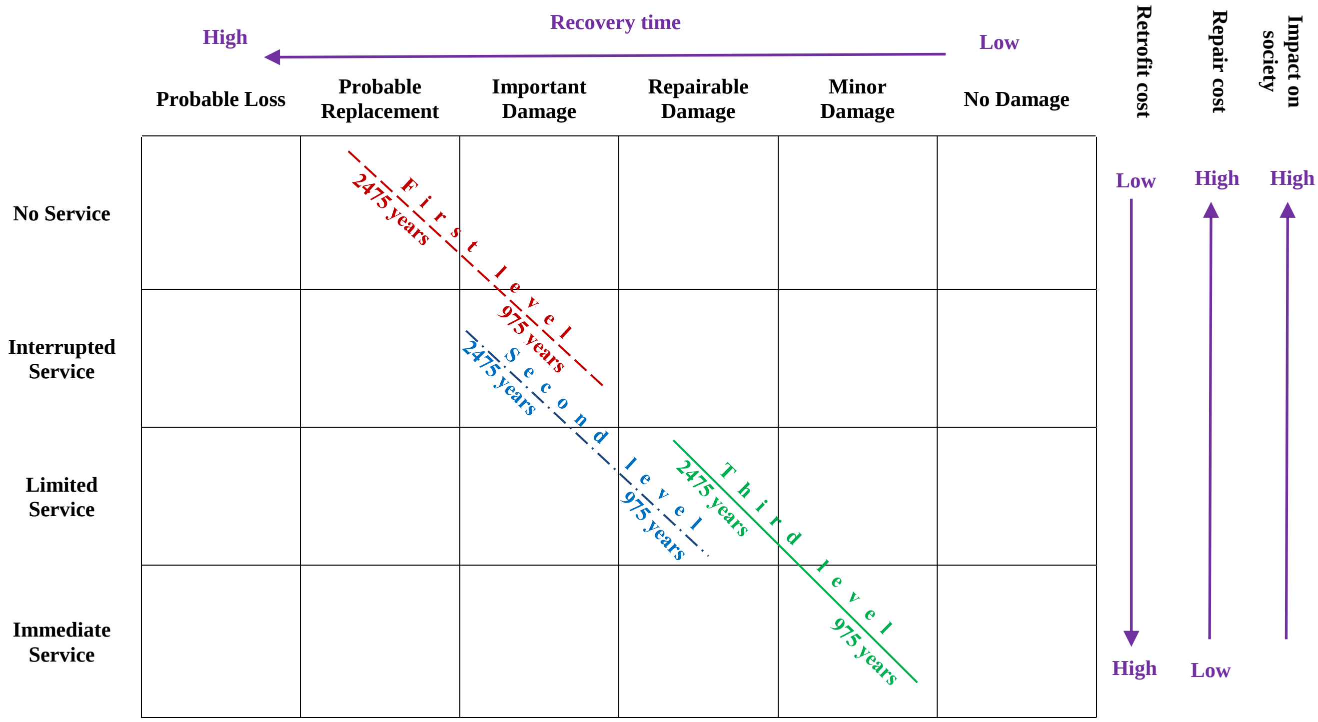

Figure 6. Three seismic retrofit levels of the Jacques Cartier bridge

Risk development

Considering the three levels of seismic retrofit, for each level, there is some seismic retrofit work to perform and some residual risk to accept after an earthquake. The goal is to achieve a satisfying balance between seismic retrofit cost and residual repair cost. It should be noted that if there is no seismic retrofit work, all the damage or risk is shifted after a major seismic event as presented in Figure 7.

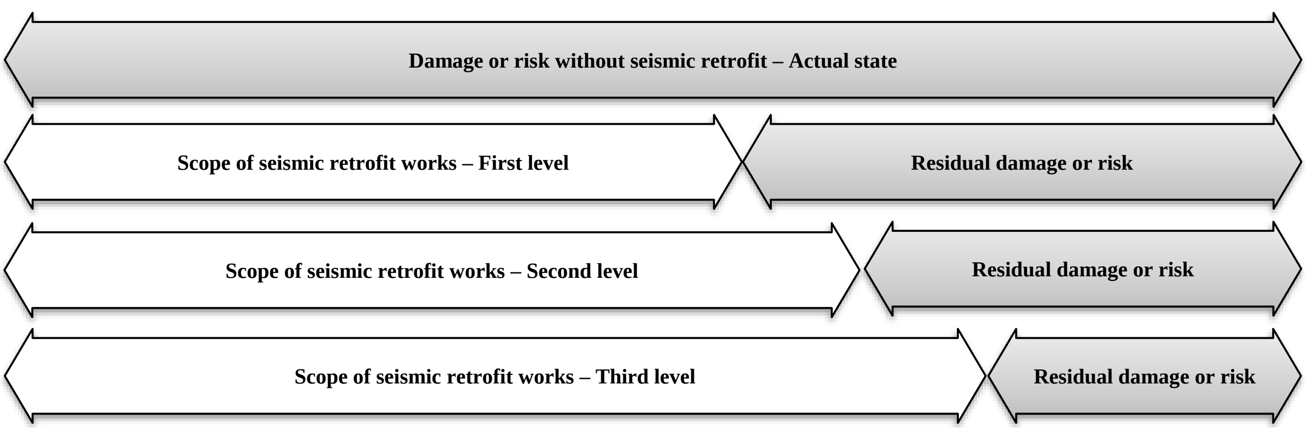

Figure 7. Risk development for three level of seismic retrofit

CONCLUSIONS

Taking into account the results of seismic performance based evaluation, it seems essential and insightful to consider a progressive and specific approach for the Jacques Cartier bridge in order to comply with the seismic retrofit work requirements.

Seismic performance evaluation carried out by the engineers led to a better understanding of the seismic behavior of the bridge. Moreover, it reveals that the seismic retrofit of the pier will probably be the most important challenge and the leading element to meet the seismic performance objectives.

Defining the required seismic retrofit work following the result of the analysis of three seismic retrofit levels will help JCCBI develop and optimize an investment plan considering the challenges and the risk related to different scenarios. However, it seems necessary to evaluate the probable residual damages for each level in order to better prepare a post-seismic action plan.

FUTURE WORK

In view of seismic performance analysis of the Jacques Cartier bridge [11], the preliminary design of the seismic retrofit will be prepared for each retrofit level by the engineers. Following the preliminary design, cost estimation and the scope of work evaluation, one retrofit level will be considered. Finally, a post-seismic action plan should be developed for a lifeline bridge like the Jacques Cartier.

ACKNOWLEDGMENTS

Throughout the different phases of this project, JCCBI engineers had the support of a technical committee that included three internationally renowned structural experts. The JCCBI greatly appreciates the support of professors Robert Tremblay and Bruno Massicotte from École Polytechnique de Montréal and professor Denis Mitchell from McGill University during the project.

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