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EVALUATING THE ECONOMIC INTEREST OF SEISMIC ISOLATION FOR SHORT AND MEDIUM SPAN BRIDGES USING A LIFE-CYCLE APPROACH

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Abstract

In several Canadian localities, the seismic hazard has a significant impact on the cost of bridges foundations. In order to mitigate the earthquake effects on the design of bridges, separating the superstructure from its foundations using seismic isolation sometimes proves to be an interesting option. But under which circumstances is seismic isolation attractive from a strictly economic point of view? This project aimed at answering this question while looking a little further than the construction costs, that is, incorporating all incurred costs over a 75 years life-cycle. The "circumstances" were defined with parameters combined in different sets, in order to represent all common bridges likely to be built in Eastern Canada. A parametric study and detailed analysis (NLTHA, POA, MMRSA) allowed for the design of each bridge case. The performance-based design approach and hazard curves from the S6-14 standard were used. From detailed analysis, the construction costs of bridges designed with, and without, isolation devices were estimated. The life-cycle costs were afterward estimated using common techniques given in the literature, but adding the repair costs following the damages caused by the probable earthquakes on the life cycle. To achieve that, fragility curves of selected bridge elements were built, using the IDA technique, and then combined in an innovative manner with the hazard curves of the localities. Life-cycle costs of the bridges were then compared in order to conclude on the bridge cases that will typically have an economic potential for seismic isolation. Orders of magnitude of the expected savings brought by seismic isolation on both the construction costs and the life-cycle costs were developed.

Keywords: seismic isolation, bridges, life-cycle cost analysis, fragility curves, earthquake engineering

1. Introduction

Seismic isolation of bridge decks is increasingly employed as an efficient method for the seismic control of bridges and the mitigation of earthquake effects on the foundations design. However, the full extent of its economic benefits is hardly available to most bridge engineers. Indeed, if not to be founded on energy-consuming calculations, an educated opinion requires for the design engineer to have past experience of isolated structures projects. The industry needed for a quick way of screening the seismic isolation opportunities for bridges to be developped and implemented in the engineering practice throughout the province.

The research project funded by the Quebec DOT is a first attempt at defining boundaries inside which employing seismic isolators in order to separate the bridge deck from its foundations generally provides an economic edge over the conventional design performed using the plastic hinges concept. It covers common small and medium span bridges of different types, built in localities having various seismic hazards.

Because seismic isolation impacts the damages suffered by the bridges in the event of an earthquake, the researsh team beleived that in order to adequatly capture the full extent of seismic isolation economic interest, one had to look further than the construction costs. Therefore the incurred costs over the full life-cycle of the bridge were assessed for several bridges, comparing for a given set of parameters a conventional design to an isolated design. The impact of seismic isolation on the construction costs, the repair costs and the maintenance costs were investigated. General boundaries and tendencies were obtained from the observation of the analysis results.

2. Methodology

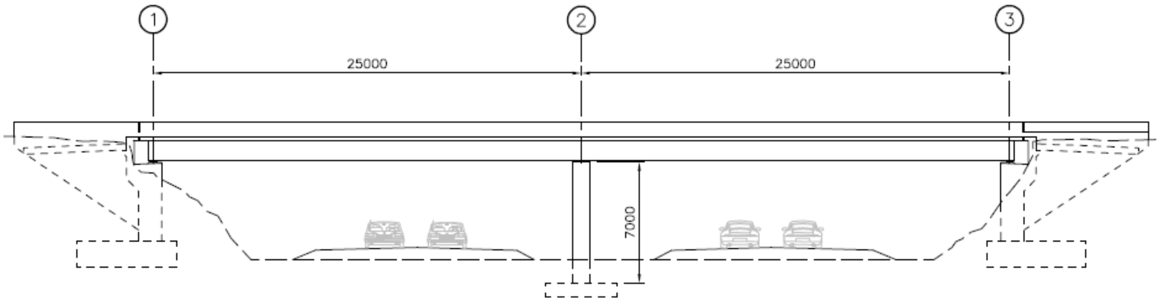
In order for the study to represent the small and medium span bridges to be designed and built, various parameters (bridge geometries, importance category, seismic hazard, deck weight, type of foundations, opening of the expansion joints) were taken into account and combined to form over 50 case study. All bridges were first designed with and without seismic isolators following the prescriptions from the Canadian Highway Bridge Design Code (CSA S6-14). The construction costs were estimated following this code-based design.

An analysis procedure was then elaborated in order to quantify the damage extent to the bridges following the probable earthquakes in three Eastern Canada areas with PGAs (1:2475) ranging from 0.38g to 1.04g, thus representing various seismic hazards. That was achieved with the valuable collaboration of *Polytechnique Montreal*.

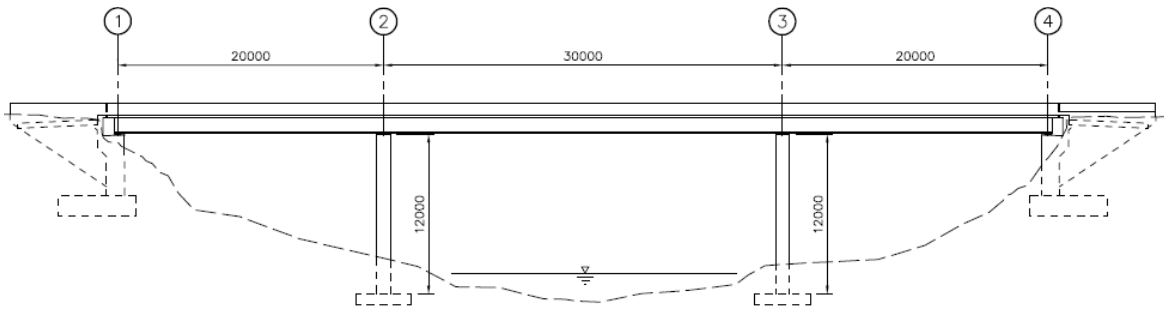
Once the repair costs associated to the probable earthquake damage quantities (over 75 years) were estimated for all bridge cases, they were integrated to the life-cycle (construction, maintenance, repair) costs estimated. That completed the life-cycle costs analysis necessary to assess the economic interest of seismic isolation for a sample large enough to be deemed representative of the small and medium span bridges to be built in Eastern Canada.

3. Characteristics of the bridges

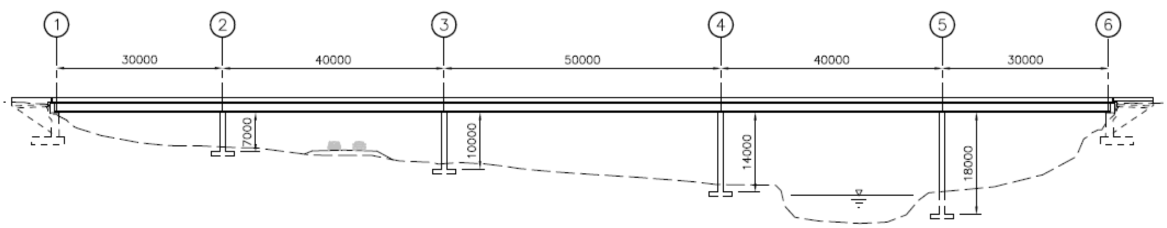
The short and medium span bridges discussed in this paper can be described with one of the three geometries shown on Figure 1, and with a set of parameters covering the seismic hazard, the importance category, the type of foundations, the deck weight and fixities, and the opening of the expansion joints. Those parameters were combined together to form a total of 56 case study, following a parametric study conducted by Maltais & al. (2012).



a) Type 1 geometry



b) Type 2 geometry



c) Type 3 geometry

Figure 1 – Bridge geometries studied

The bridges deck design was performed according to the CSA S6-14 standard. The design of the bridges foundations was carried out using a performance-based approach, following the prescriptions of the CSA S6-14 standard. It should be noted that the latter substantially differs from the previous editions, introducing well defined damage criteria (crack opening, etc.) related to performance levels. Soil-structure interaction effects were taken into account (using the finite difference method) for designing the bridges with deep foundations. No rocking effects were considered for the bridges designed with foundations bearing on the rock. Only the ductility provided by the plastic hinge was therefore taken into account for all bridge cases.

The ductility level provided by the bents plastic hinges (single curvature) was taken as R=4, as per CSA S6-14 prescriptions.

3.1 Construction costs

Let's remember this study aims at assessing the economic interest of seismic isolation on the life-cycle of short and medium span bridges, comparing the costs of conventional bridges to those of seismically isolated bridges.

The first component of the life-cycle costs consists of the construction costs; therefore they were estimated for both the conventional bridges and the seismically isolated bridges.

4 Assessment of the damages caused by the probable earthquakes

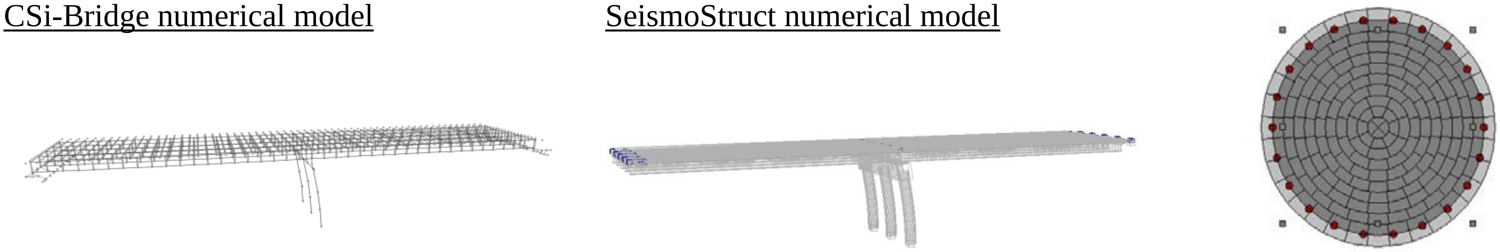
The assessment of the damage quantity, following the probable earthquakes on a 75 years life-cycle, is key to determine whether or not the seismic isolation is economically interesting. It allows for integrating the post-earthquake repair costs in the summation of the life-cycle costs, in order to get the full picture of the expected costs on the life-cycle of the bridge. First, the fragility curves of the bridge elements for which damages are expected to occur during an earthquake are obtained. Subsequently, the fragility curves are combined with the seismic hazard curves of the selected localities, which allows for estimating the damage quantities, then leading to the expected repair costs following the probable earthquakes over the 75-years life-cycle.

4.1 Numerical modeling for the nonlinear analysis

One type-1 geometry bridge was modeled with the SeismoStruct software to run nonlinear incremental dynamic analysis (IDA) of the structural system. This 2-spans bridge case was selected as the benchmark for its simple geometry that made it easier to extrapolate the analysis results to other bridge cases. The nonlinear IDA analyses allowed for studying the nonlinear behavior of the bridge, governed by the bent's columns plastic hinge modeled (Figure 2c) with fiber finite elements, for a wide range of displacement demands.

The modal analysis results obtained from a CSiBridge numerical model (Figure 2a) were compared to the SeismoStruct model (Figure 2b) results in an effort to get a good confidence level on the accuracy of the SeismoStruct model. Comparison of results showed good agreement for both the shape and the period of the first vibration mode, which contains around 95% of the deck mass.

CSi-Bridge numerical model   SeismoStruct numerical model



a) Period of 1st mode : T = 0,949 s   b) Period of 1st mode : T = 0,944 s   c) Fiber hinge geometry

Figure 2 – Numerical modeling

It should be noted that the numerical model did not include the back walls. Therefore, the displacement demand obtained at the top of the bents adequately represents only the behavior of a "Lifeline" bridge for which damage is concentrated in the plastic hinge. For "Major-route" or "Other" bridges, the damage suffered by the back wall contributes to the inelastic dynamic response, providing added damping to the system, and would need to be modeled for the analysis to be more accurate. However, neglecting the back wall effect was considered acceptable in the project global scheme, and the results obtained for the "Lifeline" benchmark bridge were extended to the "Major-route" and "Other" bridges, thus slightly over-estimating the displacement demand and the damages. The analysis was performed only in the longitudinal direction of the bridges.

4.2 Fragility curves

Fragility curves are a useful tool for assessing the seismic vulnerability of bridges. It provides the probability dispersion that a given structural element reaches or exceeds a defined damage state under a specific ground motion's intensity. It should be noted that the selected intensity measure (IM) parameter for this study is the spectral acceleration at the fundamental period ($S_a(T_1)$). This intensity measure was selected following Mackie & Stojadinovic's (2003) work and discussions with *Polytechnique Montreal*.

The seismic vulnerability of a bridge can be measured by describing the behavior of four main elements – the **bent(s)**, the **bearings**, the **expansion joints** and the **back walls**. The displacement response allows, for each of those four elements, for a good description of the behavior. In order to evaluate the displacement response of the benchmark bridge, nonlinear response history analyses were selected as the preferred method. Therefore, ground motions matching the seismic hazard of the sites considered were selected.

<u>Ground motions selection</u>

Eleven signals were selected from the Atkinson's (2009) synthetic accelerograms set using both the Uniform Hazard Spectrum (UHS) and the procedure proposed by Atkinson. In order to adequately cover the frequency content governing the dynamic response of the benchmark bridge, the period of the bridge's 1st vibration mode was considered for the selection of the accelerograms.

<u>Damage criteria</u>

In order to define the damage states, displacement-based performance criteria were selected. Adapted from Mackie & al. (2007), the method employed relies on the definition of four damage states (Table 1) to which numerical damage criteria (DC) are associated for each one of the four elements studied (bent, bearings, expansion joints, back wall). Table 2 provides an example of the bent's damage criteria.

Table 1 – Damage States

Damage state	**Description**
Light damage	Light cracking and spalling of bents and back wall concrete
Medium damage	Medium cracking and spalling of bents and back wall concrete
Important damage	Important cracking and spalling of bents and back wall concrete. Buckling of plastic hinges rebar
Failure	Failure of the bents, failure of the back wall, failure of the bearing, failure of the expansion joints

Table 2 – Summary of the bent's damage criteria

Element	**Response parameter**	**Light damage**	**Medium damage**	**Important damage**	**Failure**
Bent	Drift ratio	0,23%	2,09%	7,74%	8,33%

Nonlinear response history analyses

The nonlinear time history analyses that allowed for characterizing the behavior of the four above-mentioned elements were performed using the SeismoStruct package. In order to make sure all the previously defined damage criteria were covered with a quantity of results sufficient enough to minimize the statistical imprecision, incremental dynamic analyses (IDA) were performed. The ground motions previously described were scaled by factors from 0,1 to 2,0, with 0,1 unit increments, such that 20 analyses were completed for each ground motion. As outlined by Vamvatsikos and Fragiadakis (2009), this methodology allows for characterizing the full possible range of behaviors of the structures. In fact, in the current study, this analysis procedure allowed for describing the elastic behavior up to the yielding, the inelastic behavior, the global instability and the failure.

Results

Fragility curves are the probability dispersion, for a particular structural element, to reach or exceed a given damage state under a specified ground motion's intensity. This distribution can be described by Eq. (1) adapted from Nielson & DesRoches (2006).

$$P(DC|IM) = \Phi\left(\frac{ln\left(S_{SD}/S_{SC}\right)}{\sqrt{\beta_{SD|IM}{}^{2}+\beta_{SC}{}^{2}}}\right) \tag{1}$$

It is practical to represent those fragility curves in a graphic in order to appreciate the probability dispersion of each damage state. For example, Figure 3 shows the fragility curves for one bent of the benchmark bridge.

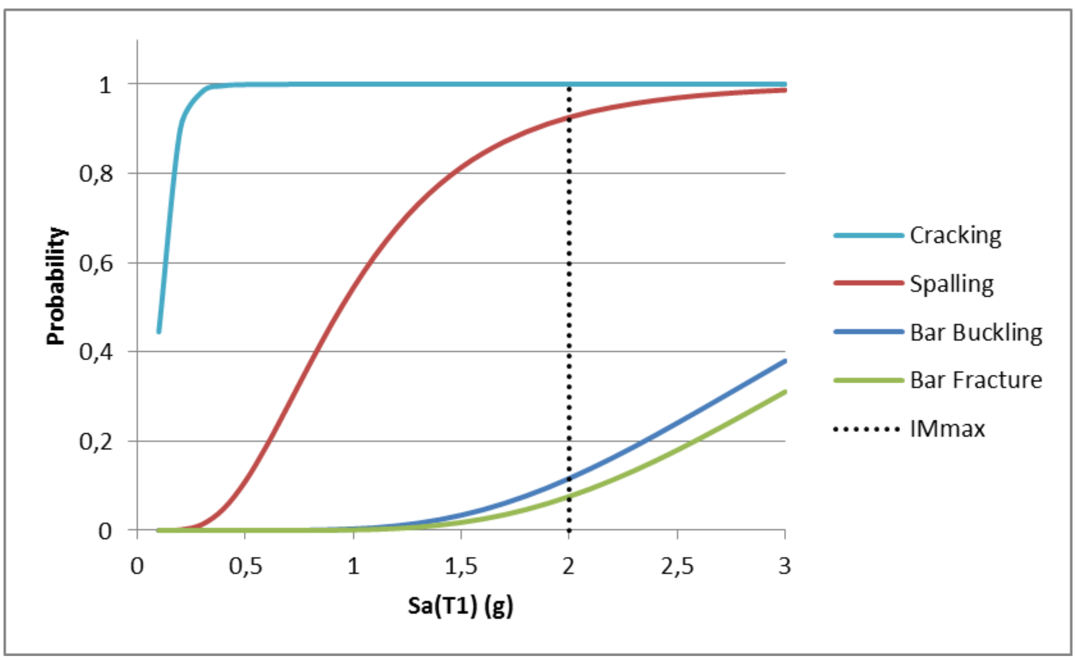


Figure 3 – Fragility curves for one bent of the benchmark bridge

4.3 Expected repairs following the probable earthquakes

Depending on the damage extent (evaluated by the previous analysis), several repair methods may be considered in order to secure the structure, bring it up to code compliance and make it resilient. Partly inspired by Mackie & al. (2007) and in accordance with the industry practice in Canada, the selected repair methods and quantities are summarized in Table 3.

Table 3 : Example of repair methods and quantities for two out of four damage states defined for the bent element

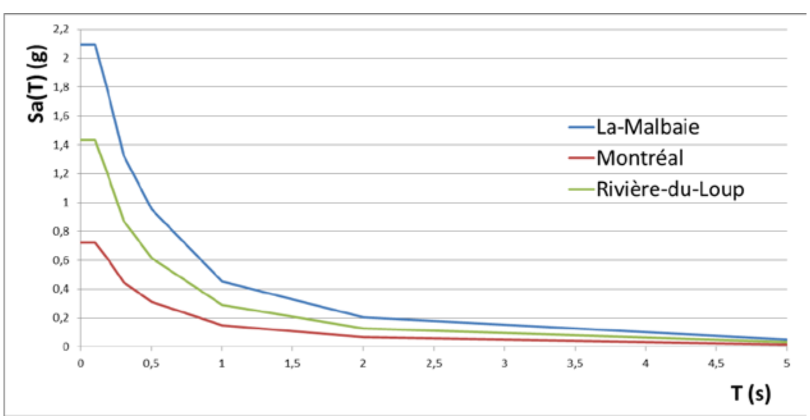
Damage states	Repair method	Repair quantity
Medium damage	Inject cracks with epoxy	4 x column heigth
	Repair concrete spalls	10 % of column surface area
Important damage	Inject cracks with epoxy	4 x column heigth
	Repair concrete spalls	25 % of the column area
	Steel column casing	Weight of the steel casing
	Galvanized rebar	25 % of the column's rebar weight
	Concrete	Concrete volume between steel casing and existing column
	Excavate	1 200 mm around the column
	Backfill	1 200 mm around the column
	Shoring	Supported length x deck width

For each element (bents, bearings, expansión joints, back walls), a combination of repair methods and quantities were associated with the damage criteria.

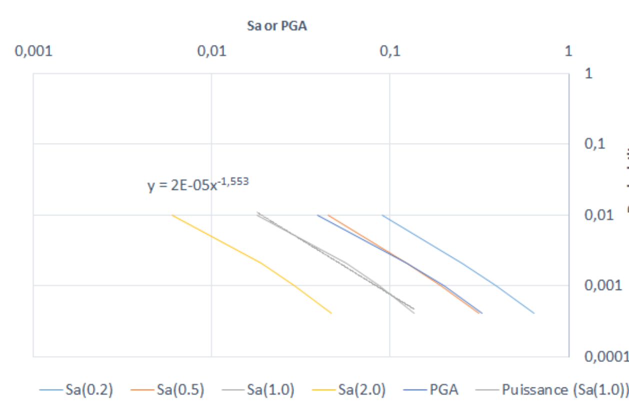
4.4 Seismic Hazard curve

The seismic hazard curve of a site describes the probability for the ground motion to reach or exceed a given intensity measure ($P(IM > x)$). Let's remember the selected intensity measure is the spectral acceleration at fundamental period of vibration ($S_a(T_1)$). The curve relating the intensity to the probability of exceedance can be described by Eq. 2.

$$(P(IM > x) = \beta \cdot x^{-\alpha} \quad (2)$$



a)



b)

Figure 4 – CAN/CSA S6-14 a) 1:2475 years Response Spectums b) Hazard curves (Montréal)

Figure 4 shows the 1:2475 years response spectrum of the localities considered in the study and an example of hazard curve.

4.5 Using the fragility curves to quantify the probable earthquake damages incurred on the bridge's life-cycle

Let's remember the fragility curves for the structural elements of the benchmark two-span bridge were calculated previously. As mentioned previously, the fragility curves provide the probability dispersion that a given structural element reaches or exceeds a defined damage state under a specific ground motion's intensity ($P(DC|IM)$). Repair methods associated to the damage criteria were subsequently developed.

Combining the data previously obtained to the probable earthquakes on the life-cycle of the bridge (probability to exceed a given motion intensity $P(IM > x)$), one can get the the repair costs to be expected on the life-cycle of a bridge following the earthquakes that are likely to happen. It should be noted that the work presented in this section is adapted from Padgett & al. (2010). It essentially consists of the combination of two probability distributions, ($P(DC|IM)$ and $P(IM > x)$), to get Eq. 3, describing the annual probability to reach a given damage criteria (DC).

$$P_{Af}(DC \mid IM > x) = \int_{x_{min}}^{x_{max}} P(DC \mid IM)(x) \cdot P(IM > x)(x) \cdot dx \tag{3}$$

In Eq. 3, x_{min} represents the intensity measure of the minimal ground motion taken into account, x_{max} is the intensity value of the maximal ground motion taken into account, and x is the intensity measure of a given ground motion.

The $P_{Af}(DC \mid IM > x)$ distribution as a function of time (f_{Tfj}) can then be obtained from Eq. 4, which represents the probability to exceed a damage criterion for a given remaining service time (T) of the structure.

$$f_{Tfj} = 1 - (1 - P_{Af}(DC \mid IM > x))^T \tag{4}$$

where j represents a given damage criterion being studied.

Then combining the distribution from Eq. 4 to the repair costs associated to the methods and quantities defined in Table 3, one can get a repair cost C_{rij}, where i is the number of the structural element under consideration. The current value (CV) estimated on the life-cycle of the bridge is defined by Eq. 5:

$$CV_{ij} = \left(\frac{1}{\propto T}\right) \cdot (1 - e^{\propto T}) \cdot -C_{rij} \cdot \left(\ln(1 - f_{Tfj}) - \ln(1 - f_{Tfj+1}\right) \tag{5}$$

where a is the inflation rate.

Summating the repair costs for a given damage criterion, then repeating for all structural elements (Figure 5 shows an example for a bent element), one can quantify the global current value (CV) of the costs incurred by the damages resulting from the probable earthquakes on the life-cycle of the bridge. Integrating those costs to the life-cycle costs analysis of a given bridge is subsequently possible.

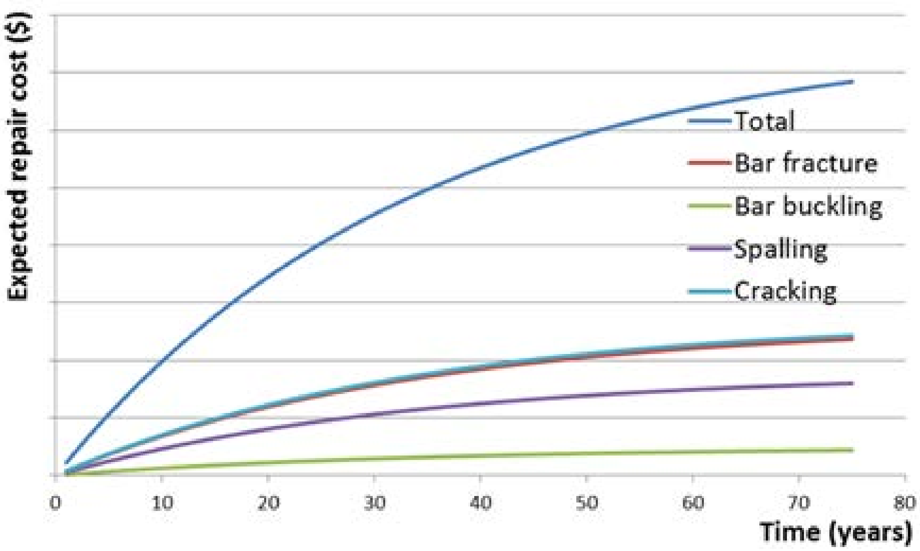


Figure 5 – Distribution of the probable repair costs per damage state (for one bent)

5. Estimating the repair costs following the probable earthquakes on the life-cycle

The repair costs of the bridges considered in this study following the probable earthquakes on the life-cycle were extrapolated from the analysis results of the benchmark two-span bridge. Let's remember the latter was designed to code requirements prior to conducting the nonlinear IDA analysis, and its construction costs were estimated accordingly. The ground motions used for the nonlinear IDA were scaled to the benchmark bridge locality (Montréal) before they were scaled by factors ranging from 0,1 to 2,0. Therefore, considering the seismic demand/capacity ratio to be constant for the design of bridges in different localities (a reasonable assumption when the bent design is governed by the seismic event), the fragility curves developed for the benchmark bridge can be considered representative of the bridges having the same overall geometry (type 1 geometry defined on Figure 1) that are built in other localities. The fragility curves obtained for the benchmark bridge can then be coupled to various hazard curves in order to determine the repair costs following the probable earthquakes on the life-cycle of the bridges (type 1 geometry) built in various localities. Under this assumption, one gets the repair costs following the probable earthquakes on the life-cycle of the type 1 geometry bridges built in diverse localities.

Three different bridges geometries were studied in this project, but the nonlinear IDA was realized only on one type 1 geometry (benchmark) bridge. The results presented herein are therefore supported by the IDA analysis results described in section 4, from which extrapolations were made on a rational basis. The "rational method" developed in order to extrapolate the aforementioned results relies on one concept that is common to the four elements under consideration: the damage is related to the deck displacement. The repair costs were estimated using the ratio (to the elements of the type 1 geometry bridges) of the construction costs for each element for the bridges having types 2 and 3 geometries. The expected repair costs following the probable earthquakes are evaluated by multiplying this ratio by the repair cost of a given type 1 geometry bridge element (see Figure 6).

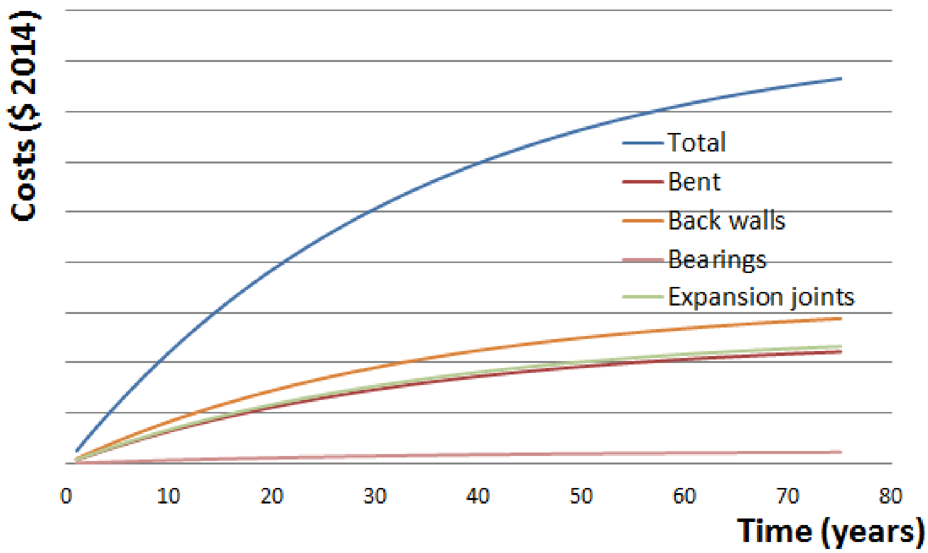


Figure 6 – Distribution of the probable repair costs per element

Performance criteria used for the design of the “Lifeline” bridges can be summarized as follow:

- For the **conventional bridges**, damage is allowed for the bents, bearings, expansion joints, and abutment back wall under the 1:2475 years earthquake. The bridges are however designed so that the expansion joints and back wall do not get damaged by the displacement demand associated to the 1:975 years design earthquake.
- For the **seismically isolated bridges**, damage is allowed for the expansion joints and abutment back wall under the 1:2475 years earthquake. The bent remains elastic. The bridges are however designed so that the expansion joints and back wall do not get damaged by the displacement demand associated to the 1:975 years design earthquake.

Performance criteria used for the design of the “Major routes” bridges are analog to those of the “Lifeline” bridge, however reducing the seismic demand by one level (no damage to the expansion joints and back walls under the 1:475 years earthquake). For the “Other” bridges, the same method is employed, reducing again the seismic demand by one more level for the design of the foundations.

6. Life-cycle costs comparison

The life-cycle cost analysis of a bridge essentially consists of the **construction costs**, the **maintenance** costs and the **repair** costs. This section summarizes the maintenance and repair costs over the life-cycle of the bridge, including the repair following the probable earthquakes. For the bridges designed with seismic isolators, it was assumed the qualification tests would be required when the bearings will be replaced (after 50 years), because the seismic loads prescribed by the Code will likely have changed. A summary of the life-cycle costs for the benchmark bridge analysed in the most severe locality is given in Table 4.

Table 4 – Expected recurrent costs over the life-cycle for a given (non-isolated) bridge case

Intervention	Intervention's frequency (years)	Intervention's value ($ 2014)	Mean annual value ($ 2014)
Operating and maintenance	1	5 000	5 000
Road lighting and signs	25	25 000	1 000
Scarring and new pavement (alternates with membrane replacement intervention)	30	45 000	1 500
Membrane replacement (including scarring and new pavement)	30	105 000	3 500
Expansion joints replacement (1 module)	30	75 000	2 500
Bearings replacement (including lifting and shoring the deck)	50	115 000	2 300
Barriers replacement	50	70 000	1 400
Painting the steel beams	50	25 000	500
Sum of the repair costs following the probable earthquakes on the life-cycle	**75**	**20 000**	**270**
		Total mean annual value:	17 970

The expected annual recurrent costs generally represent approximately 1,0% of the construction cost (constant dollars). That value is similar to the numbers obtained by others for projects of similar size and nature in North America. Adding the previous recurrent costs to the construction costs allows for comparing the life-cycle costs of the bridges. This work was achieved for the 56 cases analyzed in this study (26 conventional and 30 isolated bridges) and lead to the following observations:

- The repair costs following the probable earthquakes are not significant enough for the savings allowed by the seismic isolation to be significant. Indeed, the repair costs represent only 0,2% to 3,7% of the recurrent costs for conventional bridges, and 0,1% to 1,8% of the recurrent costs for isolated bridges. Therefore, **the seismic isolation interest can be assessed only on a construction costs basis**;
- For a given allowed deck displacement value, seismic isolation provides up to 15% life-cycle costs savings and up to 20% in construction cost savings.
- If a larger expansion joint is provided for a given seismically isolated bridge as compared to the same bridge designed in a conventional manner, seismic isolation provides up to 30% construction costs savings and 20% life-cycle cost savings;
- As expected, s**eismic isolation economic interest grows fast with the increase of the displacement allowed for the deck** (larger expansion joints). It is especially true in the localities where the seismic hazard causes large displacement demands;

The following outstanding assumptions and simplifications were realized:

- Only the Owner costs are taken into account. No indirect costs (increase in travel time, capacity loss by the road network) are recognized. Indirect costs may represent 10 to 15 times the Owner costs evaluated herein;
- Low temperature effects were not taken into account in the design of the seismic isolators and foundations;
- Only the longitudinal direction of the seismically isolated bridges is seismically isolated;

7. Further research

Some outstanding assumptions and simplifications that were necessary for this project to reach the defined objectives within the boundaries imposed by its time frame and budget are great subjects for further investigations. More specifically, the fragility analysis performed on the benchmark bridge should be performed on various bridge cases to validate the procedure that was used in order to extrapolate the results. Also, the analysis should take into account the temperature effects, if it is to be applied to northern countries. Finally, an attempt at evaluating the indirect costs for specific cases should be made. On a global note, the methodology employed for the project needs further review and some aspects need to be completed, and it has been the subject of research efforts over the last two years.

8. Acknowledgements

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