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Fragility curves for isolated bridges in eastern Canada using experimental results

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ABSTRACT

One option to mitigate the seismic risk of highway bridges in Quebec is to replace typical elastomeric bearings used there with natural-rubber seismic-isolator devices. To support this alternative, this paper assesses the seismic vulnerability of typical bridge classes retrofitted with seismic-isolator devices through the development of fragility curves. Retrofitted-bridge fragility curves provide a powerful tool to evaluate the impact of a retrofit measure on the performance of different bridge classes. The analytical fragility approach uses nonlinear time-history analysis with 3-D detailed models for typical configurations of highway bridges. Experimental results of square bearings with different sizes and shape factors are used to account for uncertainties related to the mechanical properties of seismic-isolators. Critical load tests are conducted on slender seismic isolation bearings and a finite-element model is calibrated with the test results to define the seismic-isolator limit states. The fragility curves of different key components of the bridge system are compared and the results reveal that seismic isolation is effective significantly in reducing the probability of damage to columns and foundations. Due to insufficient clearance between the superstructure and abutment wing walls, however, the probability of damage in wing walls is increased and the fragility of this component controls the bridge-system fragility for all bridge classes evaluated. Concrete-girder bridges are found to be more vulnerable than steel-girder bridges due to the larger superstructure mass involved in the seismic response. The results from this work can be used to evaluate and select bridge retrofits, and can form the basis for cost-benefit retrofit studies.

1. Introduction

The damage and losses caused by the disruption of transportation networks after recent earthquakes [1–4] have emphasized the need for risk assessment and retrofit prioritization plans for existing bridge networks. These structures are the weak link in the transportation network and their closure after an earthquake could lead to an economic crisis for some regions. Such is the case for the Province of Quebec in eastern Canada, where a significant part of its production is transported along highways [5]. This, of course, is in addition to the potential loss of life. Moreover, 75% of the bridges in Quebec are more than 30 years old [6]. They were designed without recent seismic design and detailing methods. In addition, due to new understanding of the threat by the seismology community, the design level event was increased across Canada in 2005 by the adoption of a uniform hazard spectrum with a probability of exceedance of 2% in 50 years (2500 years return period) as opposed to 10% in 50 years (500 years return period) in previous code. Fragility analysis can support insights on the relative seismic performance of highway bridges as well as the effectiveness of prospective retrofit options that aim to reduce the seismic risk to bridges given potential uncertainties in structural performance, retrofit impact, and seismic hazard.

Fragility curves describe the conditional probability that a structure or a structural component will meet or exceed a specific damage state for various levels of ground shaking. They can be derived using empirical data or analytical approaches. Empirical fragility curves have been developed based on field observation of bridge damage from past earthquakes in California [7,8] and Japan [9,10]. In regions where seismic bridge damage records are insufficient such as in the United States [11–14], eastern Canada [15], and elsewhere [16–19] analytical approaches have been used to develop fragility curves, mainly for as-built bridge configurations. A limited number of studies have been conducted to evaluate bridge retrofitting methods [20–24]. Studies by Tavares et al. [15]

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Table 1
Geometric configurations of multi-span bridges considered herein.

MSC concrete	Spans	Total length (m)	Deck width (m)	Column height (m)	Lmr[a]
Block 1	3	100.98	13.04	6.72	0.30
Block 2	3	64.79	8.35	8.35	0.52
Block 3	3	54.61	23.43	9.78	0.36
Block 4	3	75.27	17.65	4.73	0.47
Block 5	3	45.93	10.72	3.77	0.46
Block 6	3	114.49	15.23	7.80	0.32
Block 7	3	67.96	11.80	6.15	0.43
Block 8	3	89.27	16.16	4.24	0.39
MSC steel					
Block 1	3	62.24	16.5	7.18	0.48
Block 2	3	31.22	20.94	12.92	0.46
Block 3	3	127.25	11.34	6.64	0.32
Block 4	3	133.68	9.93	8.56	0.30
Block 5	3	89.74	17.62	4.24	0.44
Block 6	3	69.53	8.96	9.96	0.36
Block 7	3	49.97	15.2	3.88	0.55
Block 8	3	105.89	13.52	5.38	0.40
MSSS concrete					
Block 1	3	59.71	9.46	4.46	0.26
Block 2	3	79.67	10.13	9.81	0.31
Block 3	3	90.17	14.00	7.47	0.34
Block 4	3	46.75	13.51	3.57	0.45
Block 5	3	64.26	11.31	10.65	0.42
Block 6	3	25.90	7.91	2.72	0.49
Block 7	3	56.28	18.50	6.11	0.39
Block 8	3	95.72	15.46	5.35	0.35
MSSS steel					
Block 1	3	32.44	5.54	3.14	0.53
Block 2	3	54.29	15.64	7.64	0.26
Block 3	3	100.81	12.46	5.3	0.36
Block 4	3	103.92	8.41	5.19	0.33
Block 5	3	61.55	10.65	11.27	0.40
Block 6	3	73.4	10.32	9.51	0.45
Block 7	3	42.18	11.9	3.6	0.38
Block 8	3	66.29	15.19	6.83	0.50

[a] Ratio between middle span length and total length of the bridge.

have assessed the seismic vulnerability of typical as-built bridges in eastern Canada using analytical fragility curves. The results demonstrated that a large number of bridges may suffer significant damage after an extreme event. However, viable solutions to reduce the fragility of bridges typical to this region have yet to be explored.

The question that often arises is how to effectively mitigate the seismic risk in regions with a portfolio of bridges built prior to explicit code requirements for seismic design. Based on bridge damage observed during recent earthquakes, seismic isolation has become a viable alternative as a means for reducing bridge seismic vulnerability. This technique has been shown to be effective for the design of new bridges as well as the retrofit of existing ones [22]. The most widely accepted seismic isolation technique involves elastomeric devices [25]. Since the majority of bridges in Quebec are supported by elastomeric bearings [15] with the function of transmitting gravity loads, the flexibility needed to increase the natural periods of vibration, thus, reducing the amount of the seismic input energy into the system, can be easily obtained by designing such bearings as isolator devices [26]. Moreover, the investigation of isolated bridges based on field data records shows that isolated systems performed well against seismic forces because the use of seismic-isolators effectively decoupled the superstructure motion from the substructure, thus reducing the lateral forces applied to the substructure levels due to energy dissipation of the isolator device [27]. In an effort to mitigate the inherent seismic risk of bridges, this study proposed to replace typical elastomeric bearings with natural-rubber seismic-isolator devices. This solution, therefore, combines the advantage of using fragility curves to quantify the effectiveness of retrofit measures and the efficacy of seismic isolation in preventing seismic damage in highway bridges. The same range of values for gaps between decks and abutments presented by Tavares et al. [15] are considered in this study and no special details are adopted to respect minimal clearances for isolated bridges.

This paper presents fragility analysis considering seismic isolation with natural-rubber seismic-isolator devices as a retrofit measure. A comparison between as-built and seismic-isolated models allows an assessment of the impact of seismic isolation on the vulnerability of key bridge components as well as the system fragility for typical bridge classes in Quebec. Not only the fragility analysis framework is applied to gain new insight into the effectiveness of isolation for bridge classes in Quebec, but critical inputs to the fragility method are derived for isolated bridges based on the results of experimental data. Indeed, experimental results obtained from testing square bearings of different sizes and shape factors are used to account for the uncertainty related to the mechanical properties of seismic-isolator bearings. Critical load tests for slender bearings are used to calibrate a finite-element model and the results are used to establish the limit states for seismic-isolator bearings. The uncertainties related to the seismic hazard are considered using artificial ground-motion time histories (GMTHs) developed specifically for eastern Canada. Nonlinear time-history analyses are performed for each earthquake-bridge sample and the results are used to generate component and system fragility curves for isolated models. The fragility curves developed for isolated models provide insight into the impact of a retrofit measure on the component and system vulnerabilities for typical Quebec bridges and