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# Performance-Based Seismic Loss Assessment of Retrofitted RC Bridge Bents with Different Alternatives

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## ABSTRACT

Sustainability, measured in social, environmental, and economic metrics, can help in deciding and mitigating risks related to a bridge by fulfilling the current and future necessities. The economic metric of sustainability is the life-cycle cost of retrofitting a seismically deficient bridge bent. Consideration of life-cycle performance cost as opposed to only the initial cost for retrofitting allows funding based on risk and assists in retrofit planning of a sustainable bridge bent. Therefore, life-cycle cost analysis has been lately used to obtain an optimum retrofit for a deficient bridge bent. It considers each cost that a bridge bent can incur from rebuilding, repair, and demolition. As current code does not have performance levels and their corresponding limits for retrofitting of existing bridge bents, quantitative damage states in terms of maximum drifts under different hazard levels were developed in a previous study using incremental dynamic analyses for retrofitted multi-column bridge bents. They have been utilized to perform fragility analysis to obtain the conditional probabilities of achieving different damage states for extreme hazard level of the return period of 2,475 years in Vancouver. Two commonly used retrofitting techniques such as carbon fiber-reinforced polymer (CFRP) and concrete jackets are considered. Performance-based seismic losses of the retrofitted bridge bents have been evaluated to compare their life-cycle performances and to obtain the optimum retrofit option. The results will facilitate a meaningful understanding of performance-based seismic loss assessment of a seismically deficient bent retrofitted with CFRP and concrete jackets.

Keywords: Performance-based seismic loss; Carbon fiber-reinforced polymer; Concrete; Damage states; Fragility analysis.

## INTRODUCTION

The performance-based seismic design (PBSD) approach has been highlighted over the conventional force-based method for many years for designing bridges subjected to expected ground motion to control their deformations at global and local levels to desired levels [1]. In the PBSD approach, it is required to obtain a target drift at the selected performance level. PBSD needs prediction of damage states with confidence for the design of any structure. The conventional method only considers avoiding collapse of a structure subjected to the expected ground motion, whereas PBSD targets to control damage at different performance levels. PBSD forms the basis for measuring the life-cycle cost of retrofitting a seismically deficient bridge bent [2]. Recently, life-cycle cost assessment has become a popular tool to provide the most economic retrofit solution for such a bridge bent [2]. It not only takes into account the retrofit cost but also other costs that can be added from rebuilding, repair, and demolition.

Previous researchers considered the life cycle cost to optimize retrofits of seismically deficient bridges. The efficiencies of different retrofit options, e.g., restrainer cables and elastomeric bearings, were compared based on minimum life-cycle cost performing probabilistic seismic damage analysis of steel bridge models in Korea following first-order reliability methods [3]. Although lifetime financial objective measures were availed to obtain an optimal retrofit technique, the effects of various bridge types or hazard locations on life-cycle costs were not considered. Padgett et al. [2] proposed an approach to obtain the optimum retrofit options for four seismically deficient bridges in three locations representing different seismic hazards considering life-cycle costs and cost-benefit ratios. Seven retrofit techniques such as steel jacket, elastomeric bearing, restrainer cable, shear key, seat extender, a combination of seat extender and shear key or restrainer cable and shear key were considered in that study.

Fragility analyses of as built and retrofitted bridges for various damage states were performed and damage was related to retrofit costs. The optimum retrofit technique for a specific bridge was found to vary depending on the site seismic characteristics, as the effects of retrofit techniques at various damage states differed. Probabilistic seismic fragility analyses of a prototype bridge reinforced with steel, coupled superelastic shape memory alloy (SMA)-steel, and SMA bars, respectively, were performed to obtain the probabilities of damage at various damage states [4]. Three options for reinforcing the prototype bridge were compared based on life-cycle costs from seismic loss analyses to identify the cheapest solution. Based on the results, it was possible to obtain an optimal SMA-steel bar ratio for the coupled option to ensure a less vulnerable and more resilient bridge over the alternative techniques when subjected to earthquakes.

Canadian Highway Bridge Design Code (CHBDC) [5] highlights PBSD to control the post-seismic condition of the bridge. This code prescribes different concrete and steel strain limits for various performance levels of new bridges. Conversely, old bridges may not meet these strain limits because of deficiencies like inadequate ductility and low shear strength. Such bridges need to be retrofitted to provide desired performance under different seismic hazard levels. As the seismically deficient bridge bent considered in this study is assumed to be located in Vancouver, crustal, intra-slab, and interface earthquakes markedly influence seismic hazard, and thus were considered [5-6]. Performance-based damage states in terms of maximum drifts under different hazard levels were first developed using incremental dynamic analyses (IDA) [7] for multi-column bridge bents retrofitted with carbon fiber-reinforced polymer (CFRP) and concrete jackets in a previous study [8]. Then, they were used to perform fragility analysis to obtain the conditional probabilities of achieving different damage states for extreme hazard level of the return period of 2,475 years in this study. As no study was previously conducted to compare life cycle performances of bridge bents retrofitted with carbon fiber-reinforced polymer (CFRP) and concrete jackets, this research aims to obtain performance-based seismic losses of such retrofitted bridge bents.

## BRIDGE BENT DETAILS

This research considered a bridge bent, representative of the existing multi-column bents in Vancouver, British Columbia, Canada. The details of the bridge bent are obtained from a previous study [9]. It comprises a cap beam and three columns presented in Figure 1a. This bridge was not seismically-detailed and is considered inadequate according to current seismic performance requirements. As displayed in Figure 1b, according to CHBDC [5], the bent contains seismic deficiencies as follows: Column-column-cap beam connections without stirrups, inadequately embedded column rebars into pile caps and cap beam, and column lap-splice and plastic-hinge regions of inadequate transverse reinforcement. Eight girders, placed at equal distances from one another, are supported by the bent. A gravity load of 240 kN is transferred by each girder. Concrete compressive and reinforcement yield strengths are 21 MPa and 275 MPa, respectively.

## RETROFIT ALTERNATIVE DETAILS

A deficient bridge bent can be retrofitted using different alternatives options. Concrete jacketing costs the least among them and can also contribute to higher shear strength, ductility, lateral strength, and stiffness [10]. On the contrary, it can increase the component size in contrast with CFRP jacketing. Alternatively, CFRP is chosen over concrete thanks to its high strength, non-corrosiveness, and high modulus of elasticity [11]. Though the application of CFRP is easy, it is susceptible to fire [12]. In this research, the deficient bent was retrofitted with CFRP and concrete jackets for their economy, availability, ease of applications, and their ability to enhance seismic performance. Designs of the selected retrofit options are discussed in the next section.

### Design of different retrofit options

The bent considered for this study is assumed to belong to a major-route bridge in Vancouver, British Columbia, Canada. The site where it is located has stiff soil of Class D. The existing bent has a lateral load capacity of 1277 kN less than the required lateral capacity of 1452 kN, at the hazard level of 2,475 years return period according to CHBDC [5]. Thus, the bent was retrofitted with CFRP and concrete jackets separately such that lateral load capacities of all retrofitted bents and moment capacities of all retrofitted sections were equivalent as shown in Figure 2. Detailed designs of the different retrofit options are discussed in the following paragraphs.

This study considered CFRP having elastic modulus, tensile strength, and ultimate tensile strain of 64730 MPa, 628 MPa, and 0.01, respectively [9]. CFRP jacket thickness was obtained as 1.32 mm given an ultimate compressive strain of 0.0069 from Eq. (1) [13]. CFRP jacket was provided over the entire height of each column.

$$t_j = \frac{0.1(\varepsilon_{cu} - 0.004) D f'_{cc}}{f_{uj}\varepsilon_{uj}} \qquad (1)$$

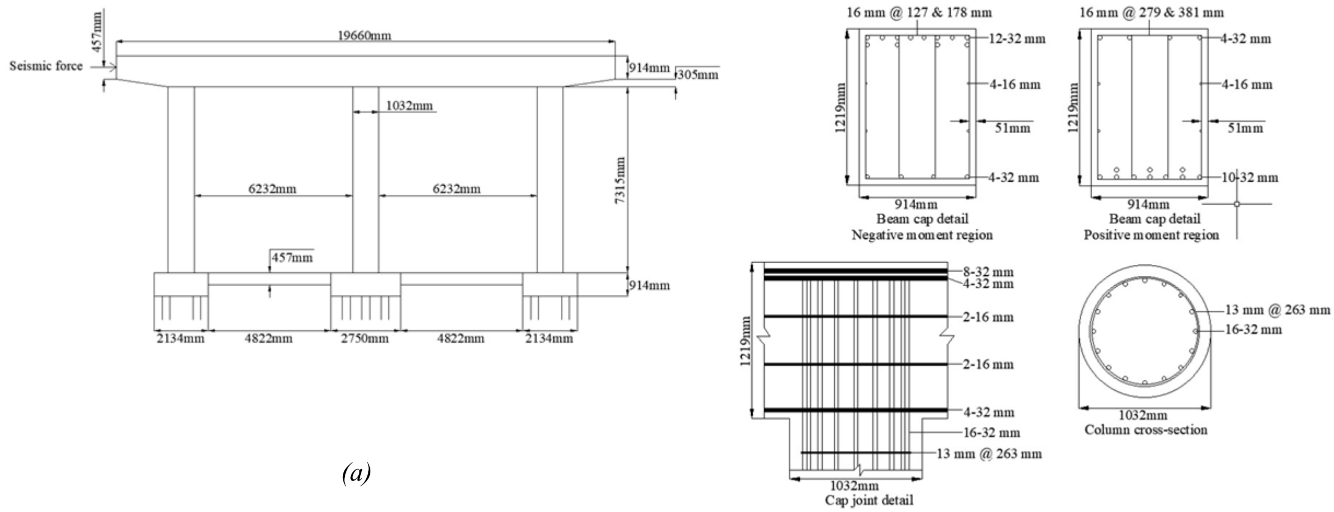
where $t_j$ = jacket thickness; $\varepsilon_{cu}$ = ultimate compressive strain; $f_{uj}$ = jacket material tensile strength; $\varepsilon_{uj}$ = jacket material ultimate tensile strain; $D$ = jacket diameter; and $f_{cc}{}'$ = confined concrete compressive strength.

Concrete jacket thickness was also obtained as 100 mm from Eq. (2) given an ultimate compressive strain of 0.0069 [13].

$$\varepsilon_{cu} = 0.004 + \frac{1.4\rho_s f_{yh}\varepsilon_{su}}{f'_{cc}} \tag{2}$$

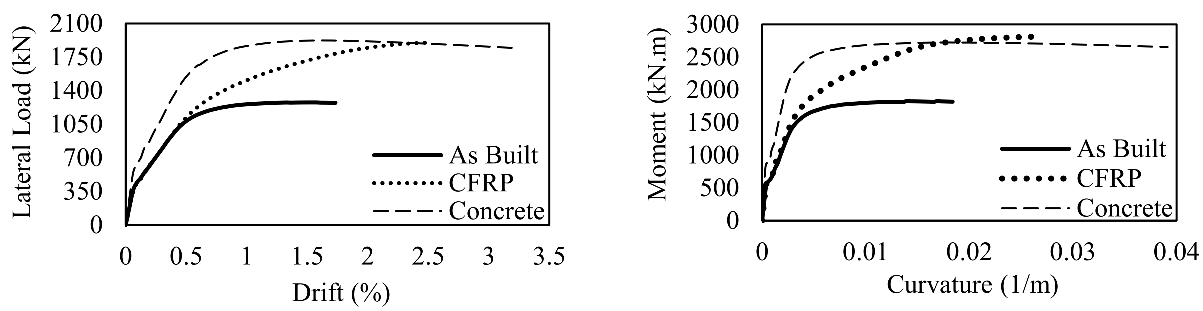
where $f_{yh}$ = transverse steel yield strength; and $\varepsilon_{su}$ = transverse steel strain at maximum tensile stress (0.15).

The concrete jacket contains twelve 20-mm diameter rebars surrounded by 10-mm diameter ties with 120 mm spacing. To be consistent, the properties of concrete, rebars, and ties of the original column were considered for concrete jacket. Concrete jackets were provided over a length of 1.68 m at top and bottom of each column to avoid spalling of concrete outside the jacketed regions.




*(a)* *(b)*

*Figure 1. Bridge bent details: (a) elevation, (b) column and cap beam cross-sections.*




*(a)* *(b)*

*Figure 2. Comparison of lateral load capacities and moment capacities of as built and retrofitted bridge bents: (a) pushover curves, (b) moment-curvature response of critical column sections.*

## FINITE ELEMENT MODELING

Columns and cap beam were modeled with fiber-based 3D inelastic displacement-based frame element in SeismoStruct [14]. The behavior of concrete, steel, and CFRP were simulated by constitutive models proposed by Mander et al. [15], Menegetto-Pinto [16], and Trilinear FIB [17-18], respectively. Time periods of deficient, CFRP, and concrete-jacketed bents were obtained as 0.60 s, 0.59 s, and 0.47 s, respectively from eigen value analyses. Outcomes from past experiments on bridge piers and bents retrofitted with CFRP and concrete were used to verify the modeling techniques in a previous study [8].

## IDA-BASED APPROACH FOR DEVELOPMENT OF PERFORMANCE-BASED DAMAGE STATES

Employing PBSD to retrofit deficient bridges requires defining the performance objectives and their corresponding damage state criteria. In a previous study [8], damage states representing various performance levels for bridge bents retrofitted using CFRP and concrete jackets were developed from the response obtained from dynamic analysis using an IDA-based approach.

## SELECTION OF EARTHQUAKES

Figure 3 presents three suites of ground motions representing three different earthquake sources and each containing 11 earthquakes. These records were used to perform IDA of the retrofitted bents. The selected earthquakes were adjusted based on extreme intensity of return period of 2475 years in Vancouver using SeismoMatch [20]. CHBDC [5]'s proposed period range of interest, 0.075–1.5 s is used to match each response spectrum with the target response spectrum. The mean spectra of three earthquake sources and the target spectrum are also shown in Figure 4.

## DEVELOPMENT OF PERFORMANCE-BASED DAMAGE STATES

In this study, different performance levels considered were cracking, yielding, and crushing, and their corresponding damage states were maximum drifts at hairline crack initiation, longitudinal reinforcement's theoretical first yield, and, core concrete's crushing, respectively. At cracking, a bridge requires no repair and thus remains fully operational, whereas at yielding it may need repair, but it still can operate after an earthquake with limited capacity. However, a bridge collapses and requires replacement when core concrete crushes.

## PERFORMANCE-BASED SEISMIC LOSS ASSESSMENT OF RETROFITTED BRIDGE BENTS

Performance-based seismic losses of bridge bents retrofitted with CFRP, and concrete jackets were evaluated to compare their

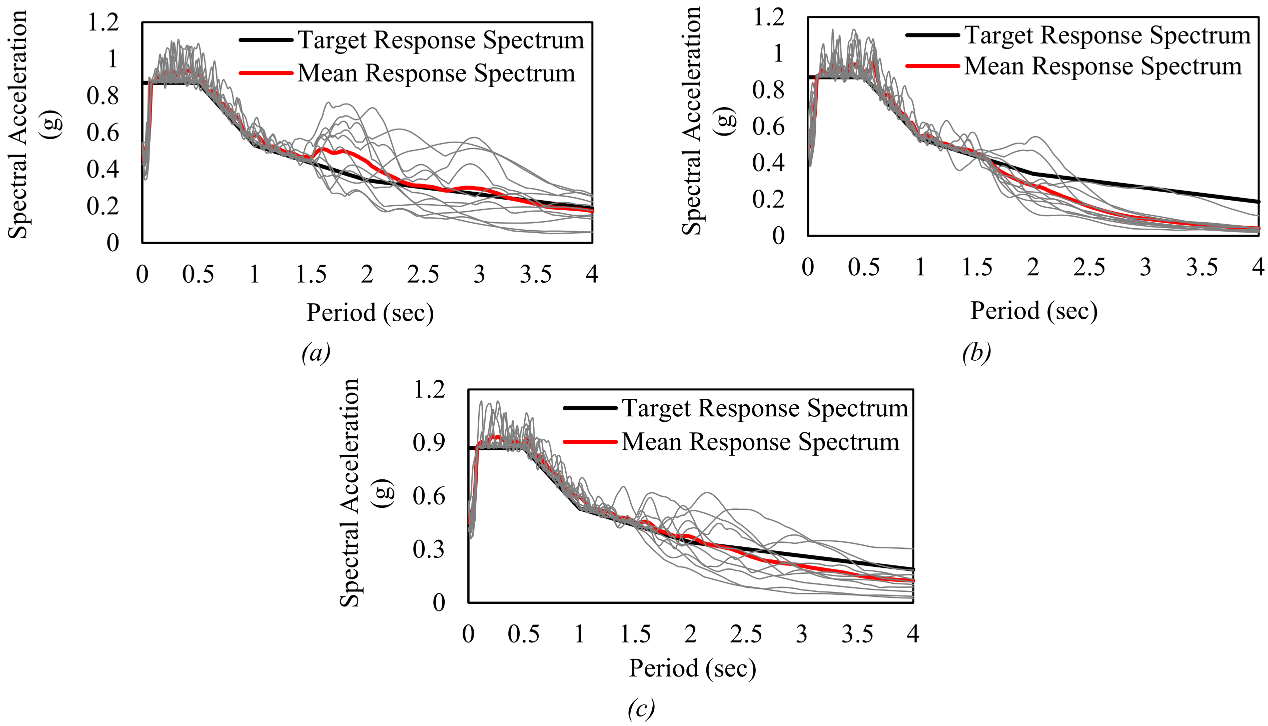



*Figure 3 Target and mean response spectra of the selected ground motions: (a) crustal, (b) intra-slab, (c) interface earthquakes.*

life-cycle performances. Thus, the fragility analysis was performed to obtain the conditional probability of achieving a particular damage state for extreme hazard level of the return period of 2,475 years using Eq. (3) [21].

$$P_{DS,i|IM} = \varphi\left\{\frac{\ln(IM)-\ln(IM_n)}{\beta_{comp}}\right\} \tag{3}$$

where $P_{DS,i|IM}$ = the conditional probability of obtaining any damage state for the considered hazard level; $\varphi$ = standard normal cumulative distribution function; $IM$ = intensity measure; and

$$\ln(IM_n) = \frac{\ln(S_c)-\ln(a)}{b} \tag{4}$$

where $IM_n$ = median value of the $IM$; ln $(IM_n)$ = natural log of the median IM value for the chosen damage state (no damage, slight, or collapse); $S_c$ = median; $a$ and $b$ are = the regression coefficients evaluated using IDA results; and the dispersion component was obtained using Eq. (5) [21]

$$\beta_{comp} = \frac{\sqrt{\beta_{EDP|IM}^2 + \beta_c^2}}{b} \quad (5)$$

where $\beta_c$ = dispersion value for the damage states of the bridge bent; and

$$\beta_{EDP|IM} = \sqrt{\frac{\sum_{i=1}^{N}\{\ln(EDP) - \ln(aIM^b)\}^2}{N-2}} \quad (6)$$

where $\beta_{EDP|IM}$ = engineering demand parameter (*EDP*)'s dispersion relying on the *IM*; and $N$ = number of simulation cases.

Values of $S_c$, $a$, $b$, and $\beta_{EDP|IM}$ were obtained from a previous study [8]. $\beta_c$s obtained using the IDA results from that study are shown in Table 1.

*Table 1. Dispersion Values for Different Performance Levels of Various Retrofit Options.*

| **Retrofit Option** | $\boldsymbol{\beta_c}$ | | |
|---|---|---|---|
| | **Cracking** | **Yielding** | **Crushing** |
| CFRP | 2.69 | 1.82 | 0.64 |
| Concrete | 2.77 | 1.96 | 0.65 |

Effects of various retrofit options on the probability of damage for different earthquake sources are shown in Figures 4-6. Here the results are compared at the design spectral acceleration of 0.87g which corresponds to an earthquake return period of 2,475 years in Vancouver. Figure 4a presents that probabilities of cracking damage are 0.88 and 0.86 for CFRP and concrete jacketed bents subjected to crustal earthquakes, respectively at the design spectral acceleration. On the other hand, they are 0.87 and 0.85 for the same bents under intra-slab earthquakes, respectively as shown in Figure 5a. However, when bents retrofitted with CFRP and concrete jackets experienced cracking for interface earthquakes, damage probabilities were 0.89 and 0.86, respectively as Figure 6a depicts. Thus, effects of earthquake sources on probability of cracking damage for each retrofit option was found to be insignificant. Besides, Figure 4b portrays that probabilities of yielding damage are 0.76 and 0.71 for CFRP and concrete jacketed bents subjected to crustal earthquakes, respectively. On the contrary, they are 0.74 and 0.69 for the same bents under intra-slab earthquakes, respectively as delineated in Figure 5b. Nevertheless, once bents retrofitted with CFRP and concrete jackets faced yielding for interface earthquakes, damage probabilities were 0.77 and 0.72, respectively as Figure 6b illustrates. Therefore, earthquake sources did not affect the probability of yielding markedly for different retrofit options. Furthermore, Figure 4c exhibits that probabilities of crushing damage are 0.15 and 0.04 for CFRP and concrete jacketed bents subjected to crustal earthquakes, respectively. Conversely, they are 0.12 and 0.03 for the same bents under intra-slab earthquakes, respectively as pictured in Figure 5c. Moreover, while core concrete of bents retrofitted with CFRP and concrete jackets crushed for interface earthquakes, damage probabilities were 0.20 and 0.04, respectively as Figure 6c displays. Consequently, core concrete of CFRP and concrete jacketed bents had the highest probability of crushing damage for interface earthquakes. However, concrete jacket reduced the probability of crushing damage for core concrete of retrofitted bent remarkably compared to CFRP one when it was subjected to crustal, intra-slab, and interface earthquakes.

Seismic loss is a sum of direct and indirect losses, expressed in terms of repair and running costs and monetary value of time loss for drivers and transported goods directed through the detour [4]. The expected annual loss of the bent ($L_i$) was evaluated using Eq. (7) [22].

$$L_i = \sum_{i=1}^{3} C_{DS,i} P_{DS,i|IM} \quad (7)$$

where $C_{DS,i}$ = direct and indirect losses; and $P_{DS,i|IM}$ = the conditional probability of obtaining any damage state for the considered hazard level.

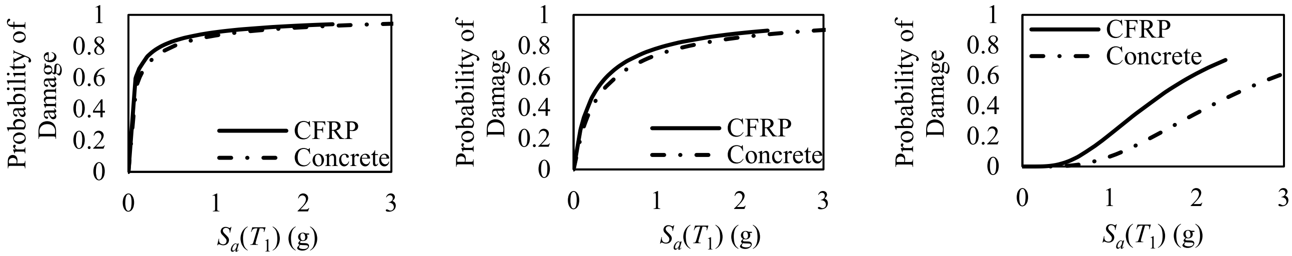
The direct loss represented by repair cost of the bent at any damage state ($C_{REP,i}$) was evaluated using Eq. (8) [23].

$$C_{REP,i} = R_{rcr} c_{reb} WL \quad (8)$$

where $R_{rcr}$ = repair cost ratios of 0, 0.08, and 0.25 [24] for performance levels: Cracking, yielding, and crushing respectively; $c_{reb}$ = rebuilding cost per unit area of the bridge; $W$ = bridge width; and $L$ = bridge length.

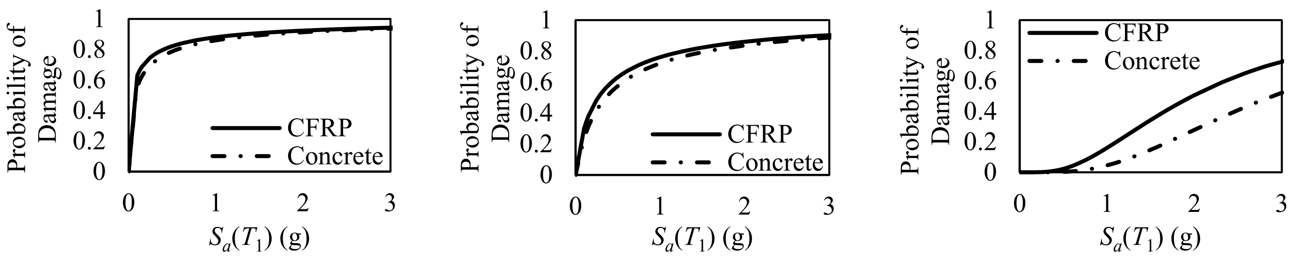
Indirect loss was measured by running cost ($C_{RUN,i}$) [25] and monetary value of time loss ($C_{TL,i}$) [23] at any damage state using Eqs. (9) and (10) respectively.

$$C_{RUN,i} = \left\{c_{run,car}\left(1 - \frac{T_0}{100}\right) + c_{run,truck}\frac{T_0}{100}\right\} D_l ADTD d_i \quad (9)$$



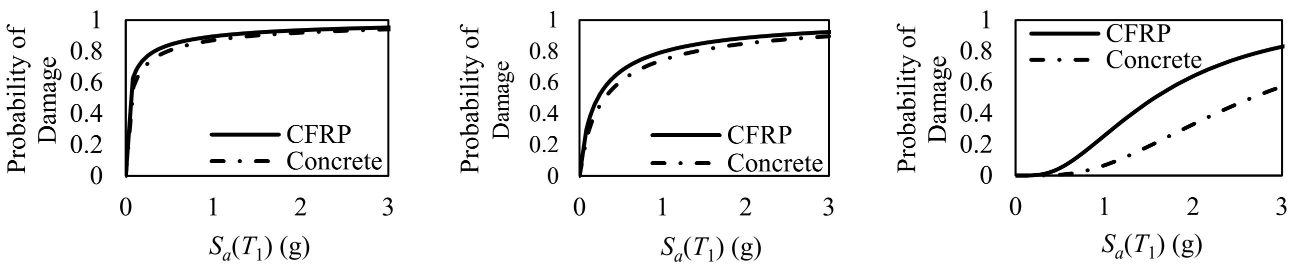

*(a)* *(b)* *(c)*

*Figure 4. Fragility curves for retrofitted bridge bent under crustal earthquakes: (a) cracking, (b) yielding, (c) crushing.*




*(a)* *(b)* *(c)*

*Figure 5. Fragility curves for retrofitted bridge bent under intra-slab earthquakes: (a) cracking, (b) yielding, (c) crushing.*




*(a)* *(b)* *(c)*

*Figure 6. Fragility curves for retrofitted bridge bent under interface earthquakes: (a) cracking, (b) yielding, (c) crushing.*

where $c_{run,car}$ = cost per unit length for car; $T_0$ = average daily truck traffic ratio; $c_{run,truck}$ = cost per unit length for truck; $D_l$ = detour length; *ADTD* = average daily traffic to detour; and $d_i$ = downtimes (times to repair the bent to full functionality) of 0, 2 (CFRP [26]) or 26 (concrete [27]), and 78 [27] days for performance levels: Cracking, yielding, and crushing respectively.

$$C_{TL,i} = \left\{c_{AW}o_{car}\left(1-\frac{T_0}{100}\right)+c_{ATC}o_{truck}\frac{T_0}{100}\right\}\left\{\frac{D_l ADTD}{S}+ADTE\left(\frac{l}{S_D}-\frac{l}{S_0}\right)\right\}d_i \tag{10}$$

where $c_{AW}$ = average hourly wage for car driver; $o_{car}$ = average occupancy for car; $c_{ATC}$ = average hourly total compensation for truck driver; $o_{truck}$ = average occupancy for truck; $S$ = average detour speed; *ADTE* = average daily traffic on the damaged route; $l$ = length of the route including the bridge; $S_D$ = average vehicle speed on the damaged route; and $S_0$ = average vehicle speed on the intact route.

Ratios of *ADTE* to average daily traffic (*ADT*) were considered as 100%, 75%, and 0% for performance levels: Cracking, yielding, and crushing, respectively [25].

The expected annual loss of the bent for the considered hazard level was evaluated by substituting Eqs. (8) – (10) into Eq. (7). An earthquake that occurs in any time interval (0, $t_{int}$) is assumed to follow Poisson's process. The total expected life-cycle loss of the bent in any time interval (0, $t_{int}$), was determined using Eq. (11) [28].

$$E\{LCL_i(t_{int})\} = \frac{\lambda_f E(L_i)}{\tau}\left(1-e^{-\tau t_{int}}\right) \tag{11}$$

where $\tau$ = monetary discount rate; and

$\lambda_f$ = mean rate of Poisson's model = $-\frac{\ln(1-P)}{\Delta t}$ [29] (12)

where $P$ = conditional probability of occurrence of earthquake in time interval $\Delta t$.

Parameter values [25, 30-35] used in Eqs. (8) – (12) are shown in Table 2.

*Table 2. Parameters Used in Seismic Loss Assessment of Retrofitted Bents.*

| $c_{reb}$ ($/m$^2$) | $c_{run,car}$ ($/km) | $T_0$ (%) | $c_{run,truck}$ ($/km) | $D_l$ (km) | $ADT$ | $c_{AW}$ ($/h) | $o_{car}$ | $c_{ATC}$ ($/h) | $o_{truck}$ | $S$ (km/h) | $\tau$ (%) | $l$ (km) | $S_0$ (km/h) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3540 | 0.32 | 10.38 | 0.47 | 2 | 66100 | 21.81 | 1.5 | 27.43 | 1.05 | 50 | 3.79 | 6 | 80 |

The total expected life-cycle losses of the retrofitted bridge bents were obtained using Eq. (11) for extreme the hazard level corresponding to a 2475-year return period event in Vancouver considering their remaining service lives 50 years. The total expected life-cycle losses of CFRP and concrete jacketed bridge bent under crustal earthquakes were found to be $27637 and $26901, respectively. On the other hand, they were obtained as $22917 and $24711, respectively when the retrofitted bridge bents were subjected to intra-slab earthquakes. However, the bridge bents retrofitted with CFRP, and concrete jackets experienced total seismic losses of $33161 and $27229, respectively for interface earthquakes. Expected annual loss of the retrofitted bridge bent has a linear relationship with the probabilities of cracking, yielding, and crushing damages according to Eq. (7). Thus, CFRP and concrete jacketed bridge bents incurred the most loss under interface earthquakes since it experienced the highest probabilities of reaching such damages states. Though, as the probability of damage at each performance level is the least, the retrofitted bridge bent experienced the smallest loss for each retrofit option under intra-slab earthquakes. Besides, the concrete jacket decreased the loss of the retrofitted bridge bent than CFRP one for each earthquake source except intra-slab since the probabilities of cracking, yielding, and crushing damages are lower for the former.

## CONCLUSIONS

The objective of this research was to assess the performance-based seismic losses of a seismically deficient bridge bent retrofitted with different alternatives such as CFRP and concrete jackets at the extreme hazard level in Vancouver considering different earthquake sources: Crustal, intra-slab, and interface. The following outcomes were obtained based on this study.

- The probability of cracking damage of each retrofit option almost remains the same for each earthquake source.
- Earthquake sources do not have notable influence on the probabilities of yielding damages for the considered retrofit techniques.
- Furthermore, interface earthquakes produced the greatest probability of crushing damage for core concrete of CFRP and concrete jacketed bents.
- Moreover, core concrete of concrete jacketed bent had markedly smaller probabilities of crushing damages than that of CFRP jacketed bent under all earthquake scenarios.
- Besides, CFRP and concrete jacketed bridge bents experienced the greatest losses for interface earthquakes, whereas they both incurred the least losses under intra-slab earthquakes.
- The bridge retrofitted with concrete jacket faced less loss regardless of the earthquake source except intra-slab.

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