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COST-EFFECTIVENESS OF SEISMIC ISOLATION AND FIBER-REINFORCED CONCRETE IN TYPICAL BRIDGE CONSTRUCTION IN CALIFORNIA

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ABSTRACT

The cost-effectiveness of innovative performance-enhancing technologies, such as seismic isolation of bridge superstructure or use of fiber-reinforced concrete materials for the construction of bridge piers, for typical highway overpass bridges in California, is investigated in this paper. A typical five-span, single-column bent reinforced concrete bridge was redesigned using these two performance enhancement strategies and modeled in OpenSees. The modeling schemes, as well as the static and dynamic analysis results of these bridge systems, are presented in a companion paper. The PEER performance-based earthquake engineering methodology was used for the computation of post-earthquake repair cost and time of the bridges. Fragility curves displaying the probability of exceeding a specific repair cost and time thresholds were developed. The total cost of the bridges included the cost of new construction and post-earthquake repair cost required for a 75 year design life of the structures. The intensity-dependent repair time loss model of the different bridges was computed in terms of crew working days representing repair efforts. A financial analysis was performed that accounted for a wide range of discount rates and confidence intervals in the estimation of the mean annual post-earthquake repair cost. Despite slightly higher initial construction costs, considerable economic benefits and structural improvements were obtained from the use of the two enhancement techniques considered, especially seismic isolation, in comparison to the fixed-base conventionally reinforced concrete bridge. The repair time of the isolated bridges was also significantly reduced.

Introduction

Research efforts in recent years have been directed to the development and implementation of innovative designs and materials in new and existing structures to enhance their seismic performance, guarantee post-earthquake serviceability, and reduce the elevated repair costs of highway bridge systems (Mosqueda *et al.* 2004; Billington and Yoon 2004; Saiidi *et al.* 2009). Cost-benefit analysis and fragility curves for bridges are a key input for performing

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seismic risk assessment and subsequent decision making regarding the inventory of bridges. Empirical fragility curves developed using bridge damage data from past earthquakes and analytical fragility curves based on dynamic analysis results, estimated damage states, and repair costs have been developed for different regions in the world. The effect of seismic isolation on fragility curves of highway bridges in Japan was assessed through an analytical study (Karim and Yamazaki 2007). Additional research studies have led to fragility curves for seismically isolated bridges in low to moderate seismic hazard regions (Shinozuka 1998; Koh *et al.* 2000; Choi *et al.* 2004). To the author's knowledge, no studies have been carried out on the effect of seismic isolation and the use of fiber-reinforced concrete on bridge fragilities in California.

The Pacific Earthquake Engineering Research (PEER) Center performance-based earthquake engineering (PBEE) framework (Cornell and Krawinkler 2000) provides a methodology for computing bridge demand, damage, and loss fragilities. The PEER PBEE framework utilizes the total probability theorem to compute the desired fragility curves by disaggregating the task into several intermediate probabilistic models with different sources of randomness and uncertainty. The computation of the loss fragility presented in the PEER PBEE framework can be carried out using a closed-form solution, numerical integration, summation, and simulation methods. Mackie *et al.* (2007) computed fragility curves based on a general closed-form solution of the PEER framework total probability integral for the repair costs of a typical ordinary standard reinforced concrete bridge designed according to AASHTO Standard Specifications for Highway Bridges (1996) and Caltrans Seismic Design Criteria (SDC) (2004). These curves relate the repair cost of the bridge as a percentage of the total construction cost to an intensity measure of a single earthquake event. The fragility curves were obtained considering different possible repair methods for the bridge and cost computation procedures, thus resulting in different discontinuous piece-wise shapes. This local linearization repair cost and time methodology (LLRCAT) was applied in the present study to compare the repair costs of isolated and fiber-reinforced concrete bridges, in comparison to conventionally-reinforced fixed-base bridge, designed according to current seismic design guidelines in California.

Construction Costs

The cost analysis presented in this paper was carried out for the fixed-base conventionally-reinforced concrete (RC), fiber-reinforced concrete (FRC), and seismically isolated (BI) bridge models implemented in OpenSees structural analysis program (Mckenna *et al.* 2000). The bridge systems consist of a typical five-span box-girder superstructure, single-column bent reinforced concrete bridge with seat abutments. The geometric and reinforcement details, modeling schemes, as well as the static and dynamic analysis results of these bridge models are presented in a companion paper. As described in the companion paper, the design of the isolated bridges was carried out for two target performance criteria, one with elastic column behavior (BI1) and the other with minor inelastic column behavior equivalent to a maximum displacement ductility demand of 2 (BI2). The cost of new construction of the different bridge models considered in this study was obtained based on the Ketchum *et al.* (2004) estimates for the RC bridge. The computation of bridge construction costs was carried out by applying unit cost from Caltrans estimates, adjusted based on current price indices for 2008Q3, to total material quantities calculated based on specifications and construction drawings. The cost of the isolation bearings is obtained based on DIS (Dynamic Isolation Systems, Inc.) and EPS (Earthquake Protection Systems, Inc.) estimates for 2008Q3, while the unit cost per pound of steel fibers is obtained from Bekaert Corporation - Dramix steel fibers manufacturer. For the particular concrete mix design used in this study no additional plasticizers or additives are required to achieve acceptable workability. Therefore, the unit cost of structural concrete casting of the FRC bridge is the same as the RC bridge cost. The mobilization and contingency costs are not considered in this study for the computation of the new construction or post-earthquake repair costs, allowing a comparison of costs without local site considerations.

The resulting costs of new construction of the RC, FRC, BI1, and BI2 bridges are presented in Table 1. The additional cost of steel fibers added to the column concrete mix and longitudinal dowels for the special plastic hinge zone detail is compensated by the reduction in the total weight of reinforcing steel bars due to the relaxation in the transverse reinforcement details. Therefore, the resulting cost of new construction of the FRC bridge is only 0.5% higher than the RC bridge. Due to the redesign of the isolated bridges with a higher volume of concrete, additional reinforcing steel weight, and high cost of the isolation bearings, the total construction cost of BI1 and BI2 bridges are 18.8 and 11.9% higher than the cost of the fixed-base RC bridge, respectively. This outcome is primarily due to the fact that in a long span bridge high quantities of materials are required for the construction of the superstructure, foundations and abutments, which were not modified for the design of the isolated bridges.

Table 1. New construction costs of RC, FRC, BI1, and BI2 bridges for 2008Q3.

Item	**RC bridge**	**FRC bridge**	**BI1 bridge**	**BI2 bridge**
Structure excavation (bridge)	\$120,769	\$120,769	\$120,769	\$120,769
Structure backfill (bridge)	\$89,765	\$89,765	\$89,765	\$89,765
Furnish piling (Caltrans Ave. Fdn. Cost)	\$104,077	\$104,077	\$104,077	\$104,077
Drive piling (Caltrans Ave. Fdn. Cost)	\$108,243	\$108,243	\$108,243	\$108,243
Prestressed cast-in-place concrete	\$294,647	\$294,647	\$294,647	\$294,647
Structural concrete, bridge footing	\$46,677	\$46,677	\$46,677	\$46,677
Structural concrete, bridge	\$1,651,188	\$1,651,188	\$1,719,376	\$1,705,788
Joint seal (type B-MR 2”)	\$9,919	\$9,919	\$9,919	\$9,919
Bar reinforcing steel	\$453,639	\$450,446	\$492,687	\$485,649
Concrete barrier (type 732)	\$80,517	\$80,517	\$80,517	\$80,517
Steel fibers	\$0	\$17,069	\$0	\$0
Lead rubber bearing isolators	\$0	\$0	\$449,056	\$264,535
Subtotal	**\$2,959,441**	**\$2,973,316**	**\$3,515,733**	**\$3,310,586**
Percent increase wrt’ RC bridge (%)	**0**	**0.5**	**18.8**	**11.9**

Methodology for Post-Earthquake Repair Cost and Time

A new vector-based probabilistic approach of applying the PEER PBEE framework to compute post-earthquake highway bridge loss models was developed by Mackie *et al.* (2007) based on the local linearization of the damage model (relationship between damage measure DM and repair quantity Q) at varying degrees of damage. In this methodology for computing bridge fragilities, the thresholds or limit-state values of decision variables (DVs) in the PEER framework are limited to direct losses such as post-earthquake repair cost and repair time for bridge components. This LLRCAT requires a data structure to organize bridge-specific repair actions, quantities, and costs. The schematic procedure of the LLRCAT methodology for a single bridge component is presented in Figure 1.

Repair cost: $$\lambda(RC > rc) = \int_{im}\int_{dm}\int_{edp} G(uc \cdot q|dm)\,dG(dm|edp)\,dG(edp|im)\,|d\lambda(im)|$$

Repair time: $$\lambda(RT > rt) = \int_{im}\int_{dm}\int_{edp} G(lpr|dm)\,dG(dm|edp)\,dG(edp|im)\,|d\lambda(im)|$$

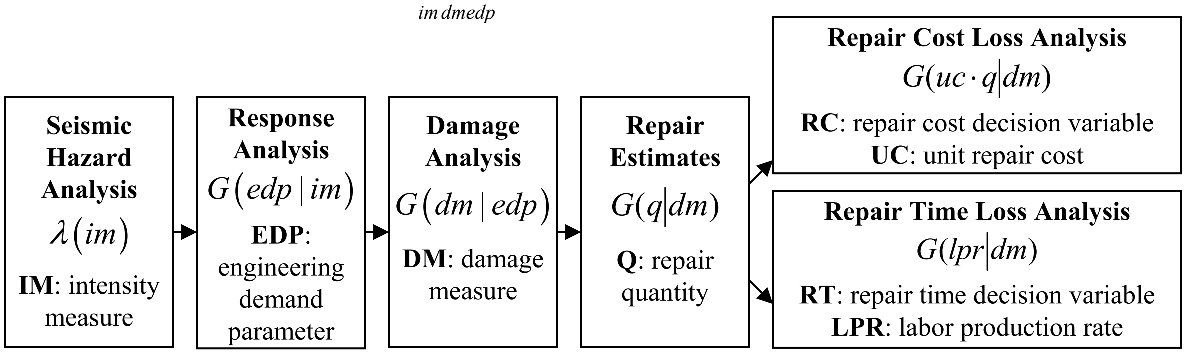

Figure 1. Schematic procedure of the LLRCAT methodology for a single bridge component.

Mackie *et. al* (2007) computed fragility curves for the repair cost and time of the RC bridge based on the LLRCAT methodology. These curves relate the repair cost of the bridge as a percentage of the total construction cost to an intensity measure of a single earthquake event such as the peak ground velocity (PGV). The repair cost ratio (RCR) obtained by normalizing the post-earthquake repair costs by the cost of original construction was used to compare the cost-effectiveness of the different bridge design options considered in this study for new construction. The LLRCAT methodology was selected in the present study to assess the cost-effectiveness of the FRC and seismically isolated bridges, compared to the fixed-base conventionally-reinforced RC bridge.

In the LLCAT methodology each bridge system was disaggregated into independent structural or non-structural components or subassemblies defined as performance groups (PGs) that are damaged, assessed, and repaired together using a specific combination of different repair methods. The damage in the PGs is characterized according to several damage states (DSs) of different engineering demand parameters (EDPs) of the bridge system. Among the main EDPs considered in this study are the maximum and residual tangential drift ratios of all four columns, maximum relative longitudinal deck- abutment displacement, maximum absolute bearing displacement at the abutments and piers (in the case of the seismically isolated bridges), maximum abutment shear key force, and residual vertical displacement of the abutments. Additional EDPs such as the strain at the roadway surface of each bridge span, residual pile cap displacement at the column and abutment foundations, and others related to the different non-structural components of the bridge systems were assumed to result in negligible contribution to the repair costs of the structures, or were excluded from the LLRCAT model due to lack of performance and cost data for these elements. Nonetheless, comparisons of the repair cost and time curves for the different bridge designs, given a site with good soil conditions, were still consistent. The EDPs for each structural PG selected for this study were computed for different IMs from the nonlinear time history analysis results using a total of 140 three-component records (see companion paper).

Discrete damage states were defined for each PG for the BI1, BI2 and FRC bridges, similarly to the RC bridge DSs and EDPs threshold in Mackie *et al.* (2007). The median, λ and standard deviation, β parameters of the lognormal distribution were defined for the cumulative distribution functions or fragility curves of each DS based on the corresponding EDP. The LLRCAT method provides a lower threshold or zero damage state (DS_0) corresponding to the onset of damage when repair costs begin to accumulate and below which the repair cost of the bridge is considered to be \$0, and an upper limit defined as an infinite damage state ($DS\infty$) corresponding to the most severe possible DS for a PG, usually complete failure and replacement of all the elements in the entire PG. The DS_0 threshold of the bearings in the isolated bridges was defined as the yield displacement estimated at 150% shear strain, while $DS\infty$ corresponding to bearing failure was estimated at 300% shear strain. The DSs corresponding to the peak tangential drift ratio EDP of the column bents include the onset of cracking in the concrete cover, spalling or crushing of the concrete cover in plain concrete and FRC, respectively, longitudinal bar buckling, and the failure of the column resulting from rebar fracture or severe concrete crushing (Mackie *et al.* 2007). Due to different cross-sectional dimensions, reinforcement details, and material properties of the column bents in the different bridge systems considered, the DS median values λ for peak tangential drift were different, as seen in Figure 2. The β values of the different PG DSs were defined similarly for all bridge systems. The DSs for the remaining bridge PGs can be found in Mackie *et al.* (2007) and Aviram (2009).

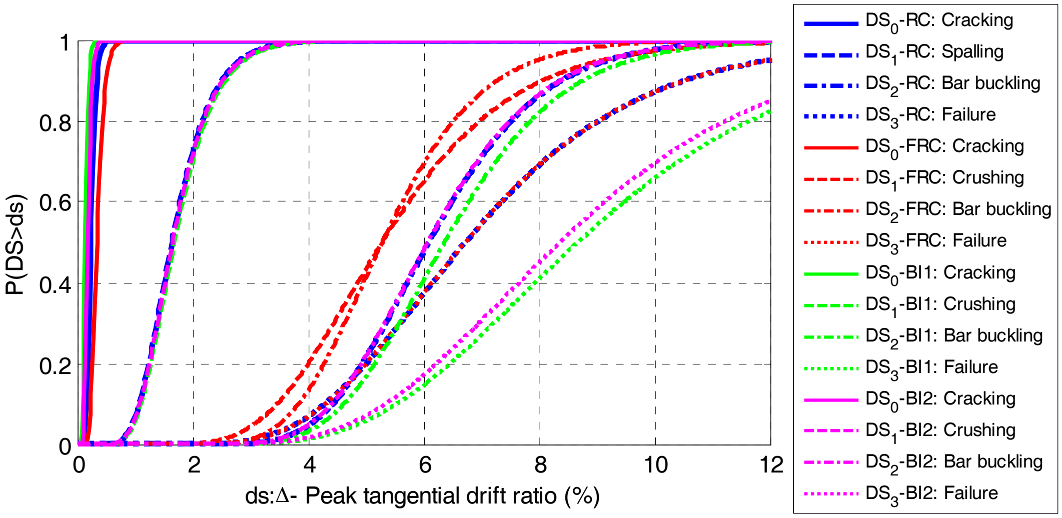

Figure 2. Fragility curves for peak column tangential drift DSs of different bridges.

Different repair methods are used by Caltrans for the various damage states of each PG or bridge component. The repair methods for each PG require a combination of several repair items, detailed in Mackie *et al.* 2007 and Aviram 2009. The PERT criterion (Perry and Grieg, 1975) is used to define the labor production rate (LPR) of each repair item in the estimation of the post-earthquake repair time of the bridges. Caltrans estimates of the durations in term of crew working day (CWD) representing one working day for a normal sized crew are used to define the LPR distributions. The repair time estimates are based on numerous simplifying assumptions for repair effort instead of repair duration, to avoid complex estimates in the latter that take into account work crew dependencies, furnishing and installation times, and critical paths.

Post-Earthquake Repair Cost and Repair Time

The resulting intensity-dependent variation in repair cost ratios (RCRs) and repair time (RT) of the different bridge types assessed using LLRCAT methodology is presented in Figure 3.

The RCR for each bridge type was computed using the corresponding estimated new construction cost for each bridge in Table 1. The final repair cost and time loss model computed by summing the costs and times from all repair items is assumed to follow a normal distribution. The RCR of the RC, FRC, BI1, and BI2 bridges at the highest hazard level plotted in Figure 3 (PGV of 200 cm/sec) is approximately 32, 17, 0.75 and 1.5%, respectively. For this intensity level (greater than 1% in 50 year probability of exceedance hazard level), the resulting repair costs of the FRC, BI1, and BI2 bridges are reduced by approximately 2, 40 and 20 times, respectively, compared to the RC bridge.

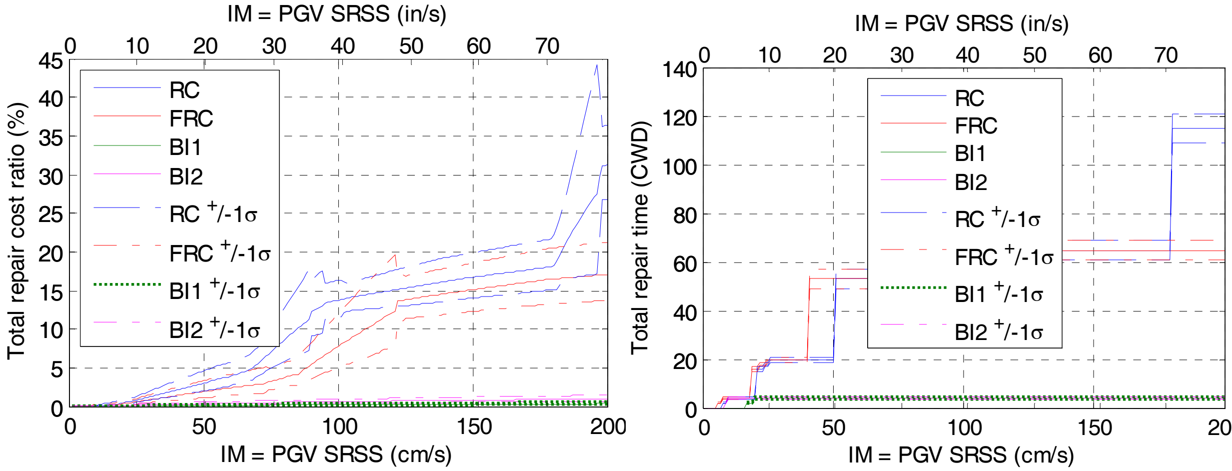

Figure 3. RCR and RT loss models for different bridges as a function of earthquake intensity.

For the RC bridge, the damage to the abutment shear keys, as well as external columns damage determined by peak tangential drift ratios control the repair cost for low hazard levels. The maximum longitudinal deck-abutment displacement resulting in abutment and approach slab damage control at the moderate hazard levels for the RC bridge, while for the high hazard levels the internal columns tangential drift is excessive and triggers high repair costs due to the need for the re-centering or replacement of the columns. For the FRC bridge, the shear keys force and peak column tangential drift had a significant contribution to the repair costs at all seismic intensities considered. At moderate intensities, the longitudinal deck-abutment displacement also contributed to the repair costs. For the isolated bridges, the PGs corresponding to maximum column tangential drift have only a minor contribution to the repair costs. Due an increased longitudinal and transverse gap size at the superstructure ends, the different abutment DSs which result in high repair costs are not triggered at any intensity level. The DSs of the remaining PGs also have a negligible contribution to the repair, thus demonstrating the effectiveness of the isolation system in reducing force and displacement demands on all bridge components.

The RCR and RT loss curves displaying the mean annual frequency (MAF) of these parameters exceeding specific thresholds were obtained by integrating over the entire range of IM considered the corresponding complementary cumulative distribution functions (ccdf) of RCR and RT curves presented in Figure 3, multiplied by the slope of the hazard curve at each IM. This seismic risk assessment was carried out for a site in Berkeley, California based on USGS hazard data. The resulting MAFs or loss curves for the RCR and RT of the different bridges exceeding different thresholds are presented in Figure 4. The mean annual RCR and RT (A_{RCR}, A_{RT}) were then computed by integrating the corresponding MAF curves over the entire range of RCR and RT thresholds considered (Der Kiureghian, 2005), as summarized in Table 2.

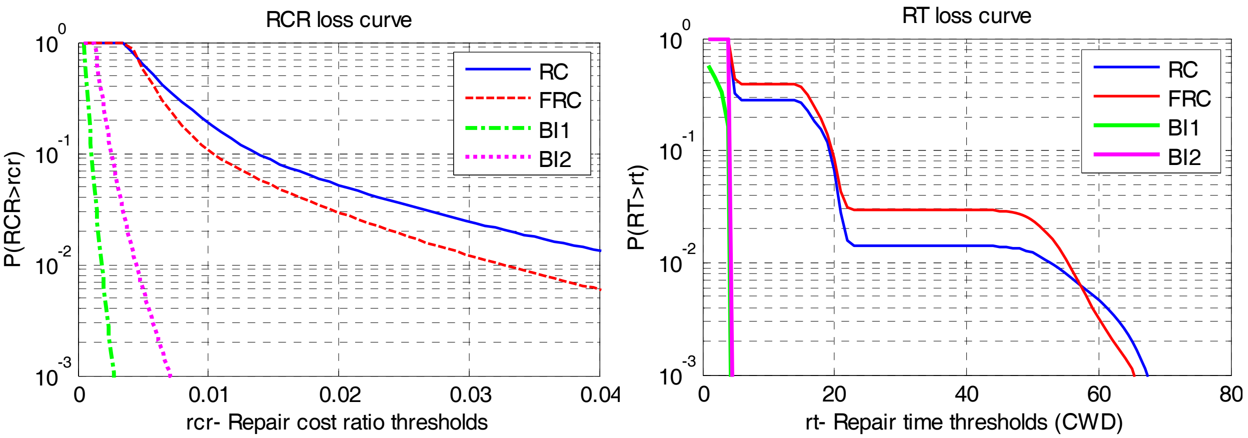

Figure 4. RCR and RT MAF or loss curves for different bridge types.

Table 2. Construction costs, repair costs, and repair time for different bridge types.

Parameter	RC bridge	FRC bridge	BI1 bridge	BI2 bridge
NC- Cost of new construction	$2,959,441	$2,973,316	$3,515,733	$3,310,586
A_{RCR}- Mean annual RCR	0.80%	0.65%	0.02%	0.13%
A- Mean annual repair cost	$23,530	$19,433	$989	$4,388
A_{RT}- Mean annual repair time	8 CWD	10 CWD	1 CWD	4 CWD

The results for the FRC, BI1, and BI2 bridges display an important reduction in the mean annual repair costs, in comparison to the baseline RC bridge. BI1 bridge is the most efficient in eliminating structural damage: it has the highest reduction in the mean annual repair costs, as much as 97% of the mean annual repair cost of the RC bridge. BI2 bridge is slightly less efficient, with a approximate reduction of 84%. The FRC bridge also provided an 18% reduction in the mean annual repair cost of the bridge system. The repair effort for the isolated bridges was also reduced significantly, requiring of only 1 to 4 CWD for the repair of minor spalling and cracking of the column bents. Furthermore, since these repair procedures are not expected to interrupt traffic on an isolated bridge, for any seismic event investigated in this study, such bridges are expected to remain in continuous operation with zero downtime and zero indirect economic losses. The mean annual repair effort for the FRC bridge was increased, in comparison to the RC bridge, from 8 to 10 CWD, primarily due to an increase in the shear key forces and abutment damage for low seismic intensity.

The total cost-effectiveness of the different bridge types considered in this study throughout their expected lifespan of 75 years was assessed by comparing their Net Present Value (NPV). The NPV of the bridges, which includes the initial construction costs, as well as the post-earthquake repair costs calculated for 75 years, is presented in Table 3 for a wide range of discount rates, i of 2-10%, and different coefficient of variations for the mean annual repair cost, A of each bridge. The present value of the total repair cost accounts only for an annual growth rate, g of 3% due primarily to inflation. The variations in the estimation of A were established in this financial model to include the effects of epistemic (modeling) uncertainty in the computation of the response estimates of the bridges, as well as other external factors which could result in a considerable reduction or increase in A. The lower and upper bounds of A were computed using different values of coefficients of variation (c.o.v.) for the assumed normal distribution. The color-coded scheme in Table 3 displays the order of total cost-effectiveness of the bridges by comparing the NPV for a given *i*-c.o.v. combination (the red, orange, green, and blue color cells represent the first, second, third, and fourth highest NPV). According to the financial analysis results, despite their high initial construction costs, the isolated bridges result in lower total costs or NPVs, compared to the RC bridge, for low interest rates and high estimates of repair cost annuity.

Table 3. Net Present Value for different bridge types with varying discount rate, *i* and coefficient of variations for the repair cost annuity, *A*.

	RC bridge				**FRC bridge**			
Confidence Intervals	**Discount rate, *i* (%)**				**Discount rate, *i* (%)**			
	2	**4**	**6**	**8**	**2**	**4**	**6**	**8**
μ-σ, c.o.v.=0.4	4,482,288	3,687,240	3,375,409	3,233,737	4,230,997	3,574,387	3,316,853	3,199,850
μ-σ, c.o.v.=0.3	4,736,096	3,808,539	3,444,737	3,279,453	4,440,611	3,674,565	3,374,110	3,237,606
μ-σ, c.o.v.=0.2	4,989,903	3,929,839	3,514,065	3,325,168	4,650,224	3,774,744	3,431,366	3,275,361
μ-σ, c.o.v.=0.1	5,243,711	4,051,139	3,583,392	3,370,884	4,859,838	3,874,922	3,488,622	3,313,117
μ- Mean	**5,497,519**	**4,172,439**	**3,652,720**	**3,416,600**	**5,069,451**	**3,975,101**	**3,545,878**	**3,350,873**
μ+σ, c.o.v.=0.1	5,751,327	4,293,738	3,722,048	3,462,316	5,279,065	4,075,279	3,603,134	3,388,628
μ+σ, c.o.v.=0.2	6,005,134	4,415,038	3,791,376	3,508,032	5,488,679	4,175,457	3,660,391	3,426,384
μ+σ, c.o.v.=0.3	6,258,942	4,536,338	3,860,704	3,553,748	5,698,292	4,275,636	3,717,647	3,464,139
μ+σ, c.o.v.=0.4	6,512,750	4,657,638	3,930,032	3,599,464	5,907,906	4,375,814	3,774,903	3,501,895

	BI1 bridge				**BI2 bridge**			
Confidence Intervals	**Discount rate, *i* (%)**				**Discount rate, *i* (%)**			
	2	**4**	**6**	**8**	**2**	**4**	**6**	**8**
μ-σ, c.o.v.=0.4	3,568,620	3,541,009	3,530,179	3,525,259	3,593,951	3,446,012	3,387,988	3,361,626
μ-σ, c.o.v.=0.3	3,577,434	3,545,221	3,532,587	3,526,847	3,641,179	3,468,583	3,400,888	3,370,132
μ-σ, c.o.v.=0.2	3,586,249	3,549,434	3,534,995	3,528,434	3,688,406	3,491,154	3,413,788	3,378,639
μ-σ, c.o.v.=0.1	3,595,063	3,553,647	3,537,402	3,530,022	3,735,634	3,513,725	3,426,688	3,387,146
μ- Mean	**3,603,878**	**3,557,859**	**3,539,810**	**3,531,610**	**3,782,862**	**3,536,296**	**3,439,589**	**3,395,652**
μ+σ, c.o.v.=0.1	3,612,692	3,562,072	3,542,218	3,533,197	3,830,089	3,558,867	3,452,489	3,404,159
μ+σ, c.o.v.=0.2	3,621,507	3,566,284	3,544,625	3,534,785	3,877,317	3,581,438	3,465,389	3,412,666
μ+σ, c.o.v.=0.3	3,630,321	3,570,497	3,547,033	3,536,373	3,924,544	3,604,009	3,478,290	3,421,172
μ+σ, c.o.v.=0.4	3,639,136	3,574,710	3,549,441	3,537,960	3,971,772	3,626,580	3,491,190	3,429,679

According to this financial model, the BI2 bridge (construction cost only 12% higher than the baseline RC bridge) is the most cost-effective of all bridge systems considered and displays the lowest NPVs for most *i*-c.o.v. combinations. The expensive BI1 bridge can be considered the most cost-efficient only for very low interest rates. Therefore, the initial increase in construction costs of the isolated bridges in the order of 19 and 12% for bridges BI1 and BI2, respectively, can be considered negligible and acceptable for the majority of financial scenarios and epistemic uncertainties considered, due to the substantial elimination of structural damage and the need for repair in all bridge components at any seismic intensity level. Since the FRC bridge is only slightly more expensive than the RC bridge and results in a reduction of 18% in the mean repair cost annuity, this bridge system presents the lowest NPV values for intermediate and high interest rates and low estimates of repair cost annuity. Similar to the BI2 bridge, the FRC bridge does not present the highest NPV values (red color cells) for any *i*-c.o.v. combination. The baseline RC is cost-effective only when interest rates are relatively high.

For each combination of interest rate and confidence interval of the repair cost annuity, a break-even analysis can be carried out, which computes the variation in the NPV of the different bridge systems over time. From the break-even analysis, the point in time (in years), at which the FRC and isolated bridges result in higher cost-effectiveness (lower NPVs) than the benchmark RC bridge, can be obtained. Figure 5 presents the break-even analysis carried out for a discount rate, *i* of 5% and the mean annual repair cost (c.o.v. = 0). For this *i*-c.o.v. combination, the FRC, BI2, and BI1 bridges become more cost effective than the cheapest RC bridge after 5, 23, and 35 years, respectively. For this average financial environment, the isolated bridges are the most cost-effective system (lowest NPVs) when the entire 75-year lifetime of the bridge structure is considered.

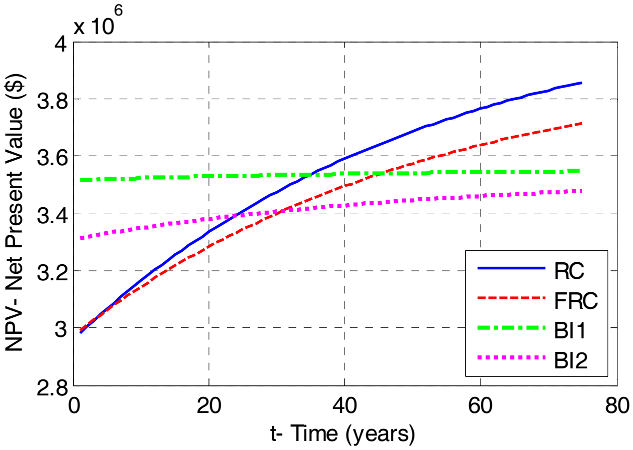

Figure 5. Break-even analysis for 5% discount rate and mean annual repair cost ratio (c.o.v.=0).

Conclusions

Two seismic performance enhancement strategies for the construction of highway bridges in California were investigated in the present study. They are: 1) the use of lead rubber bearings for the isolation of the bridge superstructure (BI bridges); and 2) the use of high-performance fiber-reinforced concrete for the construction of bridge piers (FRC bridge). The cost-effectiveness of these bridge systems were compared to a fixed-based conventionally-reinforced bridge (RC bridge), which consists of a five-span box-girder superstructure, single-column bent bridge with seat abutments. The total cost-effectiveness of the bridge systems was evaluated according to their Net Present Value (NPV), which includes considerations of their initial construction costs and total post-earthquake repair cost during an expected lifespan of 75 years, discounted using a wide range of interest rates in the financial model. The confidence intervals in the estimation of the mean annual repair cost of the bridges was also included in the financial model, computed following the PEER Center PBEE framework formula (Cornell and Krawinkler 2000) and the LLRCAT methodology (Mackie *et al.* 2007).

Despite their high initial construction costs (up to 20% greater than the RC bridge), the isolated bridges proved to be the most cost-effective for low and intermediate interest rates and for different epistemic uncertainties, due to the substantial elimination of structural damage and significant reduction of repairs in bridge components at any seismic intensity level investigated in this study. Since the repair procedures for the isolated bridges are not expected to interrupt bridge traffic, such bridges are expected to remain in continuous operation with zero downtime and zero indirect economic losses. Since the FRC bridge is only slightly more expensive than the

RC bridge and results in a reduction of 18% in the mean repair cost annuity, this bridge system results to be the most cost-effective for a financial environment with high interest rates and low estimates of repair cost annuity. However, the mean annual repair effort for the FRC bridge was slightly increased, in comparison to the RC bridge, primarily due to an increase in abutment damage at low seismic intensity. The main contribution to the repair cost and effort for the RC and FRC bridges was damage to the shear keys, the abutments and the approach slab, as well as the different damage states of the column bents: additional research focused on these bridge components is needed to better understand their behavior and to develop new designs that are more damage resistant, easier to repair and more cost effective to maintain over the expected life of a bridge.

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