OPTIMAL RETROFIT DECISION-MAKING FOR BRIDGE SYSTEMS BASED ON MULTI-HAZARD LIFECYCLE COST ANALYSIS

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ABSTRACT

Various types of hazards each with the potential to occur multiple times during the long service life of bridges may threaten the functionality of transportation systems and significantly impact the society. In hazard prone areas, as the recovery time becomes longer, the likelihood of other hazard events occurring before the system is recovered increases. This can result in the accumulation of damage and higher vulnerability of the infrastructure. This study presents a multi-hazard lifecycle cost assessment framework to find optimal solutions for retrofit strategies. The possibility of multiple occurrences of multiple types of hazard incidents is probabilistically incorporated in the framework. This methodology accurately determines the expected lifecycle cost of hazard-induced consequences by comprehensively including direct and indirect incurred costs. The presented framework is applied to a realistic multi-span reinforced concrete bridge in California that is exposed to flood and earthquake hazards. The total lifecycle cost of several practical retrofit strategies are evaluated and compared for a wide range of bridge service lives. A sensitivity analysis is also performed to characterize the impacts of several key variables on the expected lifecycle cost of the bridge and the optimal retrofit plans.

INTRODUCTION

Bridges are vital components in transportation systems. Various types of hazards each with the potential to occur multiple times during the long service life of bridges may threaten the functionality of transportation systems and significantly impact the society. Depending on the extent of induced damage, type of retrofit and repair strategy, and socio-economic factors, the recovery time after each hazard incident may vary from short to long periods. Especially in hazard prone areas, as the recovery time becomes longer, the likelihood of other hazard events occurring before the system is recovered from the previous incident increases. This can result in the accumulation of damage and higher vulnerability of the infrastructure.

In the literature of risk analysis for infrastructure systems, Life Cycle Cost (LCC) that expresses the risk of extreme events in terms of monetary loss over the service life of the system is considered as one of the most appropriate performance measures for infrastructure decision-making (*1-4*). These studies appraised system performance primarily for single hazard occurrences. For instance, LCC was applied to identify optimal decisions for the management of infrastructure systems under a single type of hazard (*5-9*). Some studies considered multiple types of hazards for decision-making of bridge systems. As an example, Patidar et al. (*10*) introduced a utility function that includes risk of hazard types as one of the weighted performance criteria for management of bridges. In these studies that consider multiple hazard incidents, it is assumed that repairs following hazard occurrences are instantaneous or there are no repair actions after each incident of hazards. In reality, however, the time required for repairing damage to infrastructures depends on the extent of damage, type of repair action, availability of materials and crew, and socio-economic factors, among others. When repair times are long, the possibility of next hazards happening before the damage arising from previous hazards are repaired, increases. This results in accumulation of damage and represents a vulnerable condition for infrastructures. For example, in September 2010, an earthquake with the magnitude of 7.1 caused widespread damage to structures and infrastructure systems in Christchurch, New Zealand (*11*). Six months later, an aftershock with the magnitude of 6.3 shook the same region and induced further damage in already damaged structures and infrastructure systems, and caused 185 casualties (*12*).

When looking at infrastructures located in regions that are exposed to more than one type of hazard, many studies, such as (*13*) and (*14*), disregard the dependency between damage conditions induced by various hazard types. Jalayer et al. (*15*) attempted to address such dependencies for multiple hazard types in a framework that requires simulating all possible scenarios for the order of hazard events of various types and intensities. In addition, each of these scenarios requires time-consuming structural pushover and dynamic analyses. These make the framework computationally prohibitive for a comprehensive LCC analysis. Moreover, there are a number of assumptions in that framework that may not accurately represent the performance of actual systems. For example, when calculating the probability of exceeding a particular damage state i at jth hazard occurrence, the dependency of damage state i to prior exceeded damage states other than i is disregarded. Conversely, any extent of prior damages directly affects the probability of exceeding damage state i at the current occurrence (i.e. jth occurrence) of the hazard event.

This study, which is an extension to the methodology developed by the authors for a single type of hazard (*16*), proposes a multi-hazard lifecycle cost assessment framework to find optimal solutions for retrofit strategies. The possibility of multiple occurrences of multiple types of hazard incidents are probabilistically incorporated in the lifecycle cost analysis framework through a recursive function that utilizes damage state-dependent fragility models and repair times. This methodology accurately determines the expected lifecycle cost of hazard-induced consequences, including repair costs of structural damage, human casualties, damage to the environment, user costs of traffic delay, vehicle operation and excess emission, and indirect economic losses due to interruptions of affected businesses. The computed lifecycle cost of hazards is discounted over the years, and added to the initial cost of applying retrofit actions and the discounted expected lifecycle cost of maintenance, to estimate the total lifecycle cost of the bridge system under study. In the rest of this paper, the analytical formulation of the suggested multi-hazard LCC is introduced. Then, the framework is demonstrated for a realistic case study bridge subjected to multiple occurrences of two types of hazards; earthquakes and floods. Finally, optimal retrofit decision-making for the case study bridge is discussed and sensitivity analysis is performed to identify some factors that significantly influence optimal retrofit decisions.

MULTI-HAZARD LIFECYCLE COST FRAMEWORK

Net Present Value (NPV) of the total LCC of an infrastructure can be typically expressed as:

$$C_{T,NPV} = C_0 + C_{M,NPV} + C_{R,NPV} \tag{1}$$

where $C_{T,NPV}$, $C_{M,NPV}$, and $C_{R,NPV}$ are the discounted NPV of C_T (total LCC), C_M (LCC of maintenance), and C_R (LCC of repair). If the LCC is evaluated for an existing system, C_0 will be zero. In case of planning to upgrade the system, this cost is equal to the cost of such upgrade. In terms of performing annual maintenance actions in the lifetime of infrastructures to keep them functioning in a healthy condition, $C_{M,NPV}$ can be represented as follows:

$$C_{M,NPV} = \sum_{t=1}^{T_{LC}-1} \gamma^t \times C_{m,t} \tag{2}$$

where $C_{m,t}$ is the maintenance cost at year t, T_{LC} is the expected service lifetime of the infrastructure, and γ is the annual discount factor equal to $\frac{1}{1+\delta}$, with δ as the interest rate.

In the lifetime of an infrastructure, the system may experience multiple occurrences of multiple types of hazards. For instance, six types of hazards have been identified significant for bridges in the state of New York: earthquake excitations, collisions, details of steel structures, details of concrete structures, hydraulic, and overload (*17*). After each such incidents, the system may experience damage or stay intact. Each condition state is followed by consequences that are typically expressed in cost terms. These costs comprise agency cost of repairing the system, user costs such as the delay cost associated with the reduced serviceability of the system during the repair process, impacts on the economy and related environmental costs, and even injuries and human casualties. In this article, these costs are referred to as repair cost.

Similar to $C_{M,NPV}$, in order to account for the discounted repair costs that are likely to incur at different times in the future, NPV of the lifecycle repair cost can also be split into yearly repair costs as follows:

$$C_{R,NPV} = \sum_{t=0}^{T_{LC}-1} \gamma^t \times C_{R,t} \tag{3}$$

where $C_{R,t}$ is the repair cost incurred at year t. $C_{R,t}$ can be further expanded to:

$$C_{R,t} = \sum_{n=1}^{N_{CS}} C_r(CS_n) \times P(CS_n, [t, t+1]) \tag{4}$$

where N_{CS} is the total number of condition states, $C_r(CS_n)$ is the repair cost when the infrastructure experiences condition state n, and $P(CS_n, [t, t+1])$ is the probability of the structure sustaining condition state n between time t and t+1. Expanding on the latter term, Equation (*4*) can be written as:

$$C_{R,t} = \sum_{n=1}^{N_{CS}} \{C_r(CS_n) \times P(CS_n, [0, t+1]) - C_r(CS_n) \times P(CS_n, [0, t]\} \tag{5}$$

Using the total probability theorem, considering that i number of hazards of various types may happen during the lifetime of an infrastructure, $C_r(CS_n) \times P(CS_n, [0, t+1])$ can be expanded as:

$$C_r(CS_n) \times P(CS_n, [0, t]) = \sum_{i=0}^{\infty} P(i, t) \times \sum_{j=0}^{i} C_r(CS_n) \times P\left(CS_n^j | i, t\right) \tag{6}$$

where $P\left(CS_n^j | i, t\right)$ is the probability that condition state n is experienced by the infrastructure at jth hazard incident if i hazards take place during [0 t]. $P(i, t)$ stands for the probability that i hazards occur during [0, t]. Equation (*6*) calculates cumulative repair costs for the entire i events that are likely to occur. Assuming independent hazard events, $P(i, t)$ is represented by Poisson distribution function as:

$$P(i, t) = \frac{\left(\sum_{h=1}^{N_H} \upsilon_h \times \mathrm{t}\right)^i e^{-\left(\sum_{h=1}^{N_H} \upsilon_h \times \mathrm{t}\right)}}{i!} \tag{7}$$

where υ_h stands for the occurrence rate of hazard type h, and N_H represents the total number of hazard types that may hit the infrastructure throughout its lifetime.
In terms of available information from fragility curves, which is a common practice in structural reliability, $P\left(CS_n^j | i, t\right)$ for one type of hazard can be written as:

$$P\left(CS_n^j | i, t\right) = P\left(LS_n^j | i, t\right) - P\left(LS_{n+1}^j | i, t\right) \tag{8}$$

where $P\left(LS_n^j | i, t\right)$ is the probability that limit state n is exceeded by the infrastructure at jth hazard incident, if i hazards take place during [0, t]. This information can be extracted from structural fragility curves. Considering uncertainties in structural response, structural repair status at the time of jth hazard incident (whether complete or yet incomplete), the condition state of the structure at the time of jth hazard incident, and the intensity of the jth hazard incident, $P\left(LS_n^j | i, t\right)$ can be articulated as follows (*15*):

$$
P\left(LS_n^j|i,t\right) = \sum_{n'=1}^{N'} \sum_{RP} \sum_{IM} P(LS_n^j|\left[RP_{n'}, CS_{n'}^{j-1}\right], IM, i, t) \times P\left(\left[RP_{n'}|CS_{n'}^{j-1}, i, t\right]\right) \\ \times P(CS_{n'}^{j-1}|i,t) \times P(IM) \tag{9}
$$

where N' is the total number of condition states, RP is the repair status (either complete or incomplete), and IM is the intensity measure of the hazard incident. $\left[RP_{n'}, CS_{n'}^{j-1}\right]$ represents the condition state of the infrastructure at the time of *j*th hazard incident, which is considered as intact if the repair process is complete, or condition state n' otherwise. Extending Equation (*9*) to multiple hazard types with the possibility of the infrastructure experiencing multiple types of damage, $P\left(LS_n^j|i,t\right)$ is modified to $P\left(LS_{[n_1,\ldots,n_M]}^j|i,t\right)$ which can be expressed as:

$$
P\left(LS_{[n_1,\ldots,n_M]}^j|i,t\right) \\ = \sum_{n_1'=1}^{N_1'} \cdots \sum_{n_M'=1}^{N_M'} \sum_{h=1}^{N_H} \sum_{RP} \sum_{IM_h} P(LS_{[n_1,\ldots,n_M]}^j \left|\left[RP_{[n_1',\ldots,n_M']}, CS_{[n_1',\ldots,n_M']}^{j-1}\right], HT_h, IM_h, i, t\right) \\ \times P\left(\left[RP_{[n_1',\ldots,n_M']}\middle|CS_{[n_1',\ldots,n_M']}^{j-1}, HT_h, i, t\right]\right) \times P(CS_{[n_1',\ldots,n_M']}^{j-1}|i,t) \times P(HT_h) \times P(IM_h) \tag{10}
$$

where $P\left(LS_{[n_1,\ldots,n_M]}^j|i,t\right)$ is the probability of exceeding condition state $[n_1, \ldots, n_M]$ at *j*th hazard occurrence given *i* hazards take place within time [0, *t*]. These terms are called *limit state transition probabilities* in this paper. N_M' is the total number of condition states for damage type *M*, N_H is the total number of hazard types that may hit the system, RP is the repair status (either complete or incomplete) for each of the *M* damage types, and IM_h is the intensity measure of hazard type *h*. Having the knowledge of the repair status for each probabilistic realization in Equation (*10*), $P(LS_{[n_1,\ldots,n_M]}^j \left|\left[RP_{[n_1',\ldots,n_M']}, CS_{[n_1',\ldots,n_M']}^{j-1}\right], HT_h, IM_h, i, t\right)$ can be calculated based on fragility curves. For some realizations, this information should be available when the infrastructure is in a damaged condition. Thus, damage state-dependent fragility curves should be available for the infrastructure under study. It can be shown that $P(CS_{[n_1',\ldots,n_M']}^{j-1}|i,t)$ in Equation (*10*) can be expressed in terms of exceedance probabilities of limit states as follows:

$$
P\left(CS_{[n_1,\ldots,n_M]}^j|i,t\right) \\ = P\left(LS_{[n_1,\ldots,n_M]}^j|i,t\right) \\ - \sum_{\substack{i_1\in\{0,1\} \\ (i_1,\ldots,i_M)\neq(0,\ldots,0)}} \cdots \sum_{i_M\in\{0,1\}} P(LS_{[n_1+i_1,\ldots,n_M+i_M]}^j|i,t) \\ + \sum_{k=2}^{2^M-1} (-1)^k \times \binom{2^M-1}{k} \times P\left(LS_{[n_1+1,\ldots,n_M+1]}^j|i,t\right) \tag{11}
$$

Then, based on Equation (*10*) and inserting the right hand side of Equation (*11*) in Equation (*10*), $P\left(LS^{j}_{[n_1,\ldots,n_M]}|i,t\right)$ can be recursively calculated. This procedure is the key to the time efficiency of the proposed framework, while the realizations of a wide range of uncertain variables are comprehensively integrated. Since hazards of different types are considered independent, $P(HT_h)$ is enumerated as:

$$P(HT_h) = \frac{\upsilon_h}{\sum_{h'=1}^{N_H} \upsilon_{h'}} \tag{12}$$

Finally, in Equation (*10*), $P\left(\left[RP_{[n'_1,\ldots,n'_M]}\middle|CS^{j-1}_{[n'_1,\ldots,n'_M]}, HT_h, i, t\right]\right)$ stands for the probability of a given repair status i.e. complete or incomplete. This term is calculated depending on the events of:

- condition state of the structure that hazard of type *h* will affect,
- the likelihood of the hazard that is happening at *j*th hazard incident, and
- the time span [0, *t*] during which *i* number of hazards should take place.

IMPLEMENTATION OF THE FRAMEOWRK FOR A CASE STUDY BRIDGE

The suggested framework is implemented for a realistic five span Reinforced Concrete (RC) bridge located in the city of Sacramento, over American river. The bridge model was developed and analyzed by Prasad and Banerjee (*18*). The bridge is vulnerable to both seismic–induced damages and flood-induced scour accumulations. Following NIBS, FEMA (*19*), Prasad and Banerjee (*18*) categorized seismic–induced damages based on the displacement ductility capacity of bridge piers. As the scour depth of bridge piles increases, the capacity of the bridge against seismic-induced damage decreases. However, the accumulation of seismic damage in the bridge does not affect the scour depth induced by flood events.

For the suggested LCC framework with the discount rate of 5%, combinations of retrofit alternatives including no retrofit, applying steel jacketing, and performing scour countermeasures are considered, and optimal retrofit decisions for various service lifetimes of the case study bridge are determined. The repair process for any seismic-induced damage starts following each earthquake event. For the case of flood hazard, the scour countermeasure, if implemented, will be applied at the start of decision-making time horizon. For retrofit alternatives where no scour countermeasures are performed initially, scour depth accumulates as the number of flood events increases. The required input information for the implementation of the proposed framework for the case study bridge is briefly discussed hereafter.

Hazard Curves

Flood and earthquake hazard curves for the location of the bridge are adopted from Prasad and Banerjee (*18*) and Peterson et al. (*20*), respectively. These curves are shown in Figure 1, and are required for the generation of limit state transition probabilities according to Equation (*10*).

Damage State-Dependent Fragility Curves

Considering four scour-levels of 0.0 m, 0.6 m, 1.5 m, and 3.0 m, and five ductility capacity levels for bridge piers (0.0 (no damage), 2.25 (minor), 2.90 (moderate), 4.60 (major), and 5.0 (complete or collapse)), there are 20 limit states for hazard-induced damages. The statistical characteristics of these damage state-dependent fragility curves for the case study bridge are taken from Prasad

(*21*), Prasad and Banerjee (*18*), and engineering judgment of the authors. Flood-induced damages, on the other hand, only contain the foregoing four scour-levels. Expected scour depths caused by various flood discharge levels were determined in Prasad and Banerjee (*18*) for the case study bridge, and are utilized in this study.

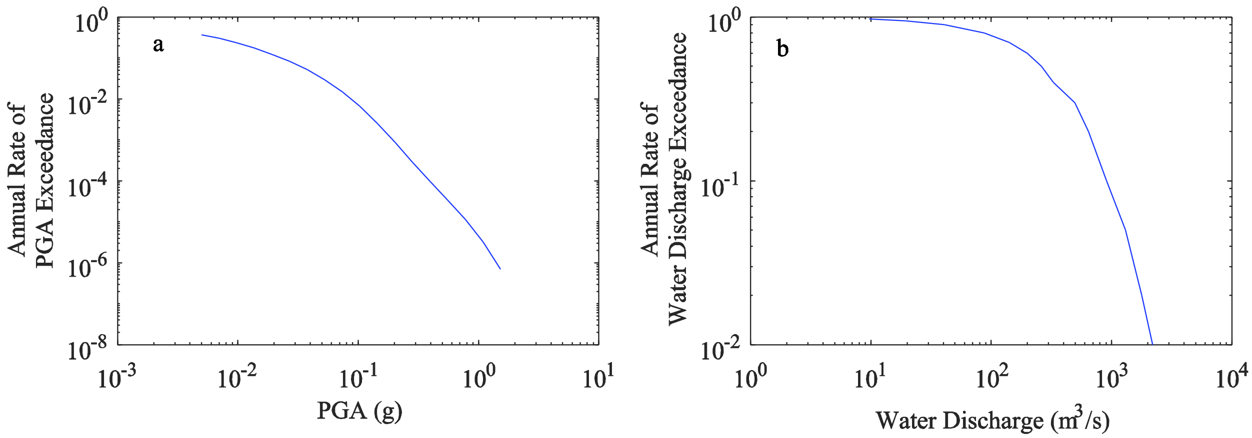

FIGURE 1 a) Seismic (*20*) and b) Water Discharge (*18*) Hazard Curves for the Location of the Case Study Bridge

Required Repair Times for Damage States

One of the major features of the proposed framework is the ability to consider damage state-dependent repair times in the LCC calculations. Based on the repair path for each hazard-induced damage-state, lognormal mean and standard deviation of the required repair times are identified from NIBS, FEMA (*19*), Gordin (22), Shinozuka et al. (23), Burton et al. (24), and authors' judgement.

Cost Terms

Initial Cost of Retrofit Actions

Retrofitting or performing a scour countermeasure plan adds an initial cost to the total LCC of the bridge. Based on Caltrans historical data, Venkittaraman and Banerjee (*25*) reported \$2/lb for the cost of retrofitting piers of a bridge with steel jacketing. On this basis, the total cost of steel jacketing for all piers of the case study bridge is estimated as \$383,420.

The scour countermeasure plan considered for this bridge is concrete-grouting the voids of the loose soil underneath each pile foundation and the soil surrounding bent foundations together with 1 m layer of Rock Slope Protection (RSP) material. Following Caltrans (*26*), the cost of performing this countermeasure plan for the four pile-foundations of the case study bridge is estimated as \$195,000.

Annual Maintenance Cost

The annual cost of maintenance for the case study bridge is determined from the average cost of major repairs and rehabilitations for a sample of bridges in the city of Rancho Santa Margarita, CA (*27*), considering these costs are repeated every 15 years. On this basis, annual maintenance cost is estimated as 7.5% of the bridge replacement cost. According to Caltrans construction statistics, the expected cost of replacement of the case study bridge is \$1833/m^2 (*8*).

Cost of Consequences for Damage States

Agency Cost of Repairing the Physical Damage

Following NIBS, FEMA (*19*) and in line with the seismic damage states considered by Prasad and Banerjee (*18*), the cost of repairing minor, moderate, major, and collapse damages are 0.03, 0.08, 0.25, and 1.00 times the bridge replacement cost, respectively. In addition, 10% and 20% of the bridge repair cost are added to incorporate mobilization and contingency costs, respectively.

Cost of Delay on Users, Vehicle Operations, and Excess Gas Emission

As a consequence of partial/complete closure of the bridge for repairing the physical damage, cost of delay on users, extra vehicle operations, and excess gas emission (emission of hydrocarbons, carbon monoxide, and nitrogen oxide) are incurred (*28*). The total cost of such consequences are denoted by C_{DVE}. The unit cost of these consequences after updating to year 2016 is $21.79/hour and $58.83/hour for unit cars and trucks, respectively (ODOT, 2010). The general formulation for the calculation of these costs is:

$$C_{DVE} = \tau_n \times (t_{ij}^{D/R} - t_{ij}^{O}) \times [(AADT - AADTT) \times \rho_C + AADTT \times \rho_T] \tag{13}$$

where $AADT$ and $AADTT$ are the annual average daily traffic and annual average daily truck traffic of path *ij* that the bridge is part of, τ_n is the recovery time for damage state *n*, t_{ij}^{O} is the original time for passing path *ij* using the main bridge with no partial/complete closure and speed reduction, and $t_{ij}^{D/R}$ is the time for passing path *ij* using the main bridge/detour with partial/complete closure and speed reduction. The AADT of the bridge is considered as 77,000 for the three lane Capital City highway (*29*), which crosses the American River in the Sacramento County. The terms $t_{ij}^{D/R}$ and t_{ij}^{O} are calculated following the procedure presented by Bocchini and Frangopol (*30*).

Indirect Cost of Economic Losses

As a result of interruptions due to complete/partial bridge closure for repair actions, business activities neighboring the bridge get affected. Following a study by Kliesen (*31*), twice the C_{DVE} is considered for the indirect cost of economic losses.

Cost of Human Casualties

Human injuries and deaths are potential consequences of incurred damages to bridges. Dividing the severity of these consequences into four levels, according to NIBS, FEMA (*19*), the general formulation to quantify these adverse consequences, C_H, is:

$$C_H = \sum_{i=1}^{4} C_{SL_i} \times CR_n^{SL_i} \times NPAR \tag{14}$$

where C_{SL_i} denotes the cost of human casualty for severity level *i* (extracted from Porter et al. (*32*), $CR_n^{SL_i}$ stands for the casualty rate for severity level *i* (given in NIBS, FEMA (*19*)) and condition state *n*, and $NPAR$ is the total number of people at risk (estimated based on relations presented by Caltrans (*33*)).

Cost of Damage to Environment
Air pollution, consumption of energy, and the possibility of global warming due to excess emission of carbon dioxide is a consequence of extra gas consumption by vehicles that are delayed by partial/complete bridge closure. The cost of these implications, C_E, can be generally formulated as:

$$C_E = C_{Env} \times \tau_n \times AADT \times \left[l_{ij} \times En_{V_{ij}} + \sum_{b \epsilon ij} s_{b,ij} \times l_{b,ij} \times En_{V_{b,ij}} - l_{ij} \times En_{V_{ij}^O} \right] \quad (15)$$

where l_{ij} and $l_{b,ij}$ are the length of the path *ij* through the main highway and detour b, respectively. $En_{V_{ij}^O}$, $En_{V_{b,ij}}$, and $En_{V_{ij}}$ denote the unit value of carbon dioxide emission at speeds V_{ij}^O, V_{ij}, and $V_{b,ij}$, which are the average velocity of vehicles traveling from point *i* to *j* passing through the main highway before interruption by partial/complete road closure, the main highway after interruption by partial/complete road closure, and detour b, respectively. These values are extracted from the study conducted by Gallivan et al. (*34*). Finally, C_{Env}, the unit cost of environmental damage, is considered as \$33.49 per ton for year 2016 (*35*).

NUMERICAL RESULTS
The framework is implemented for the case study bridge to determine optimal retrofit actions for a wide range of decision-making time horizons. In this regards, four retrofit alternatives are considered:

- Status Quo: The bridge is planned to operate as is.
- No ScC with SJ: No scour countermeasure plans are performed on the bridge, while all bridge piers are strengthened using steel jacketing.
- With ScC and No SJ: No steel jacketing is performed on bridge piers, while the scour countermeasure plan described in the previous section will prevent bridge foundation from undermining throughout its lifetime.
- With ScC and with SJ: Both steel jacketing and scour countermeasure retrofit plans are implemented on the bridge.

The numerical results are provided in Figure 2. Figure 2-c shows that the maintenance costs of the four retrofit alternatives are relatively close, however as expected, this cost is slightly more for costlier retrofit actions. Figures 2-b and 2-c also show that if no retrofit plan is performed on the bridge, the LCC of repair is more than the LCC of maintenance; this indicates the significance of considering the risk of hazards in the total LCC calculations. Figure 2-b also indicates that retrofit alternatives with ScC and with SJ, no ScC with SJ, and with ScC and no SJ are the most effective strategies in reducing the risk of hazards in the lifetime of the bridge. However, since performing these plans are initially costly, none of these plans are optimal if the lifetime of the bridge is less than 30 years (see Figure 2-a). That is, within the range of [0, 30] years of decision-making time horizon, status quo is optimal, which results in the least LCC among all alternatives. It is worthy to mention that if the effect of multi-hazard is ignored in the LCC analysis, i.e. equivalent to zero LCC of repair, the agency is not motivated to take any retrofit action for the bridge for any decision-making time-horizon, since retrofit plans are initially costly. However, the proposed multi-hazard framework identifies no ScC with SJ as the optimal strategy for lifetimes beyond 30 years. This results in $79,000 less incurred LCC, if the decision-making time-horizon is 75 years.

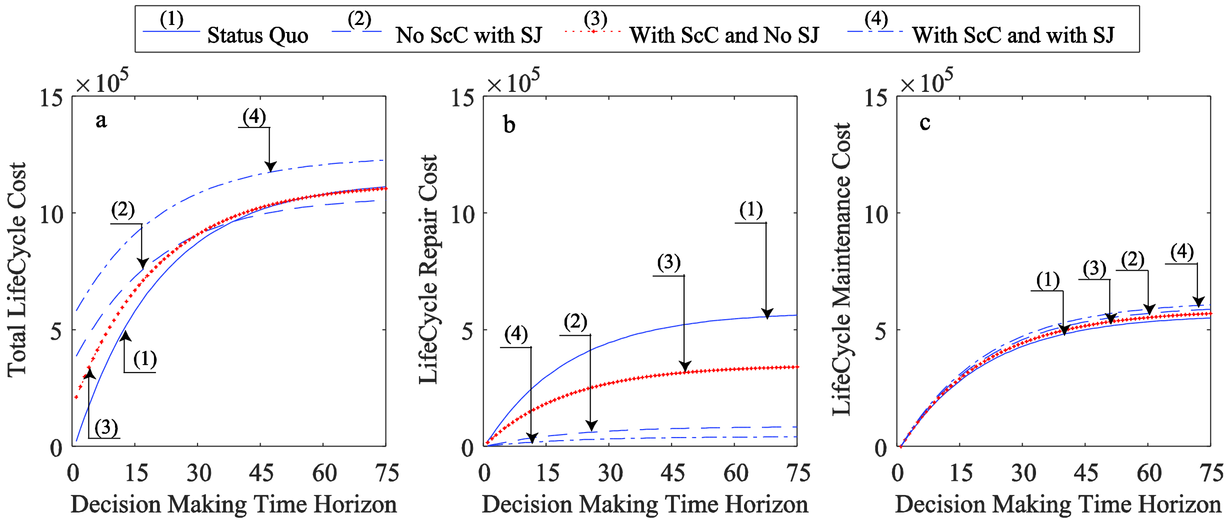

FIGURE 2 Expected a) Total b) Repair c) Maintenance LifeCycle Cost of Various Retrofit Alternative for the Case Study Bridge

As the discount rate increases, the effect of future costs on the LCC of the bridge diminishes. This might affect optimal decisions for long-term decision-making time-horizons. Considering three values of discount rate, ranging from 1% to 7% (suggested by Beck et al. (*37*)), variation of the total LCC and optimal retrofit plans for the four retrofit alternatives are evaluated in Figure 3. As a general trend, increasing discount rate reduces the total LCC. This reduction is more significant for the status quo retrofit plan. Since the long-term LCC of repair for this alternative is more than other retrofit plans, reduction in discount rate reduces these long-term costs more for the status quo plan compared to other strategies. This makes status quo the optimal policy for the entire considered decision-making lifetimes, if the discount factor is 7%. On the other hand, if the discount rate is as low as 1%, implementing no ScC and with SJ results in minimum lifecycle cost.

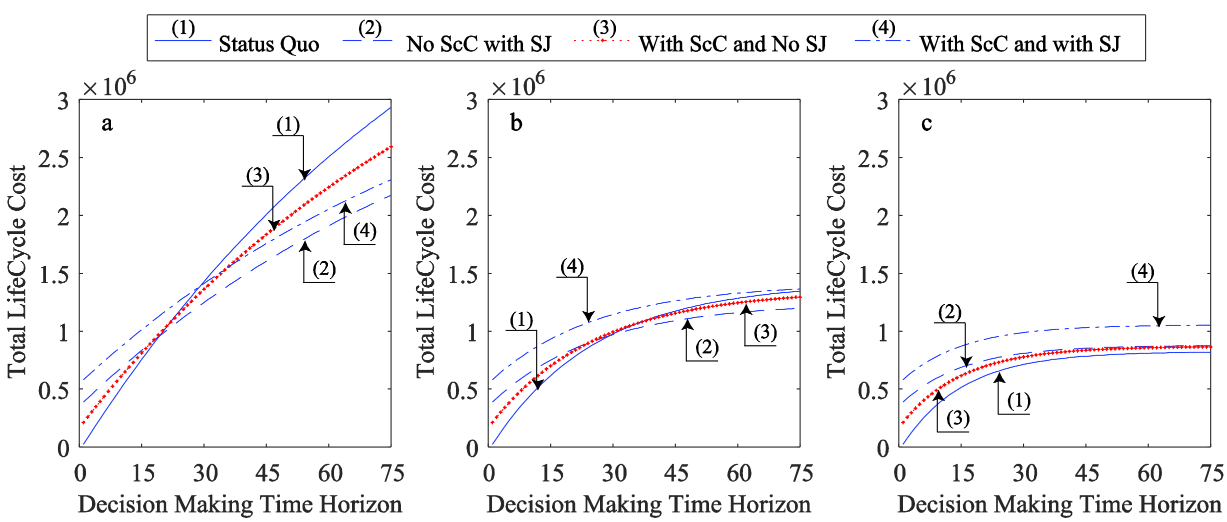

FIGURE 3 Total LCC of Various Retrofit Alternatives with Respect to Discount Rates of a) 1% b) 4% and c) 7%.

In Figure 4, effects of the variation of repair times and AADT on the total LCC of the bridge are shown. The repair times, as a function of each damage state, may vary based on the availability of crew and materials, damage to the nearby infrastructure, and preparedness of the agency in responding to the incurred damages, among others. Based on the statistical characteristics of the repair times described in the previous section, using a Latin Hypercube sampling technique, the required repair times corresponding to non-exceedance probabilities of 0.00, 0.50, and 0.95 are calculated for each damage state n, i.e. T_0^n, $T_{0.5}^n$ and $T_{0.95}^n$. In other words, T_α^n is calculated such that the probability of the required repair time at condition state n less than T_α^n is α, where $\alpha = \{0, 0.5, 0.95\}$. Figure 4-a shows as the required repair times increases, the incurred LCCs grows significantly. For example, the total LCC corresponding to $\alpha = 0.95$ is almost twice the total LCC in the case where $\alpha = 0.00$ (representing instantaneous repairs), when the decision-making time-horizon is 75 years. In Figure 4-b the variation of LCCs with respect to three AADT values corresponding to 0.00, 0.40, and 0.80 times the traffic capacity of the bridge reported by Zegeer et al. (*36*), i.e. $AADT_\delta$ with $\delta = \{0.00, 0.40, 0.80\}$, is depicted. The results show that LCC values increase considerably with the passing traffic on the bridge in such a way that the total LCC corresponding to $AADT_{0.80}$ becomes as high as three times the total LCC associated with $AADT_{0.00}$, when 75 years of service lifetime is expected from the bridge.

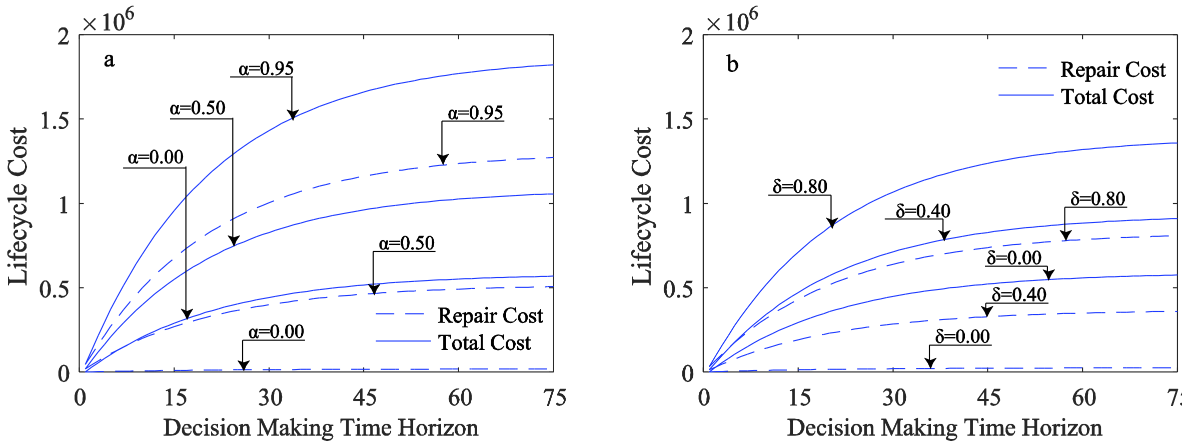

FIGURE 4 Sensitivity of the Total and Repair LCC of the Status Quo Retrofit Alternative with Respect to Variations in a) Repair Time Durations b) Annual Average Daily Traffic

CONCLUSIONS

This study proposes a multi-hazard lifecycle cost assessment framework to find optimal solutions for retrofit strategies. The possibility of multiple occurrences of multiple types of hazard incidents are probabilistically incorporated in the lifecycle cost analysis framework through a recursive function that utilizes damage state-dependent fragility models and repair times. The proposed recursive algorithm is the key to the time efficiency of the framework, which makes it feasible for applications in practice. This methodology accurately determines the expected lifecycle cost of hazard-induced consequences, including repair costs of structural damage, human casualties, damage to the environment, user costs of traffic delay, extra vehicle operation and excess emission, and indirect economic losses due to interruptions of affected businesses. The computed lifecycle cost of hazards is discounted over the years, and added to the initial cost of applying retrofit actions and the discounted expected lifecycle cost of maintenance, to estimate the total lifecycle cost of the bridge system under study.

The presented framework is applied to a realistic multi-span RC bridge in California exposed to flood and earthquake hazards. The total lifecycle cost of several practical retrofit strategies, including steel jacketing of the entire columns and scour countermeasures are evaluated and compared. Considering a wide range of decision-making lifetime horizons for the bridge system under study, the optimal strategies are found as:

- performing no retrofit action, when the expected lifetime is less than 30 years.
- applying steel jacketing to bridge columns, if the decision-making service lifetime of the bridge is between 31 and 75 years.

These optimal policies result in the least total lifecycle cost. This optimization scheme assures optimality in both the incurred costs and safety of the bridge users. A sensitivity analysis is also performed to characterize the impacts of several key variables on the lifecycle cost values and the optimal retrofit plans. It is shown that lower discount rates, higher required repair times, and larger traffic volumes on the bridge significantly increase the total LCC of the bridge. It is also found that the optimal plan may change as the above variables change. Given the capabilities offered by the proposed methodology, it can greatly help decision-makers in identification of optimal retrofit strategies with higher confidence, and enables them to invest on factors that reduce the lifecycle costs the most.

REFERENCES

1. Chang, S. E., & Shinozuka, M. Life-cycle cost analysis with natural hazard risk. *Journal of infrastructure systems*, 2(3), 1996, 118-126.
2. Goulet, C. A., Haselton, C. B., Mitrani-Reiser, J., Beck, J. L., Deierlein, G. G., Porter, K. A., & Stewart, J. P. Evaluation of the seismic performance of a code-conforming reinforced-concrete frame building—from seismic hazard to collapse safety and economic losses. *Earthquake Engineering & Structural Dynamics*, 36(13), 2007, pp 1973-1997.
3. Padgett, J. E., Dennemann, K., & Ghosh, J. Risk-based seismic life-cycle cost–benefit (LCC-B) analysis for bridge retrofit assessment. *Structural Safety*, *32*(3), 2010, pp 165-173.
4. Frangopol, D. M. Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges 1. *Structure and Infrastructure Engineering*, 7(6), 2011, 389-413.
5. Yeo, G. L., & Cornell, C. A. Post-quake decision analysis using dynamic programming. *Earthquake Engineering & Structural Dynamics*, *38*(1), 2009, 79-93.
6. Veneziano, D., Agarwal, A., & Karaca, E. Decision making with epistemic uncertainty under safety constraints: An application to seismic design. *Probabilistic Engineering Mechanics*, *24*(3), 2009, 426-437.
7. Freddi, F., Padgett, J. E., & Dall'asta, A. Life Cycle Cost Analysis of Low Ductility RC Frame Buildings Retrofitted by Modern Retrofit Techniques. 2012.
8. Yilmaz, T., Banerjee, S., & Johnson, P. A. Performance of two real-life California bridges under regional natural hazards. *Journal of Bridge Engineering*, 2015, 04015063.
9. Chandrasekaran, S., & Banerjee, S. Retrofit Optimization for Resilience Enhancement of Bridges under Multihazard Scenario. *Journal of Structural Engineering*, 2015, C4015012.
10. Patidar, V. Labi, S., Sinha, K., Thompson, P. *Multi-objective optimization for bridge management systems* (Vol. 67). Transportation Research Board. NCHRP Report 590, 2007.

11. BBC news. *Strong earthquake rocks New Zealand's South Island*. 2010. Accessed url: http://www.bbc.com/news/world-asia-pacific-11183685.
12. New Zealand Police. *Christchurch earthquake. List of deceased*. 2012. Accessed url: http://www.police.govt.nz/major-events/previous-major-events/christchurch-earthquake/list-deceased.
13. Wen, Y. K., & Kang, Y. J. Minimum building life-cycle cost design criteria. II: Applications. *Journal of Structural Engineering*, *127*(3), 2001, 338-346.
14. Decò, A., & Frangopol, D. M. Risk assessment of highway bridges under multiple hazards. *Journal of Risk Research*, *14*(9), 2011, 1057-1089.
15. Jalayer, F., Asprone, D., Prota, A., & Manfredi, G. Multi-hazard upgrade decision making for critical infrastructure based on life-cycle cost criteria.*Earthquake Engineering & Structural Dynamics*, *40*(10), 2011, 1163-1179.
16. Fereshtehnejad, E. and Shafieezadeh, A., Multiple hazard incidents lifecycle cost assessment of structural systems considering state-dependent repair times and fragility curves. *Earthquake Engineering & Structural Dynamics*, *45*(14), 2016, pp.2327-2347.
17. Shirole, A.M. and Loftus, M.J., Assessment of Bridge Vulnerability to Hydraulic Failures. *Transportation Research Record*, 1992, 18-24.
18. Prasad, G. G., & Banerjee, S. The impact of flood-induced scour on seismic fragility characteristics of bridges. *Journal of Earthquake Engineering*, *17*(6), 2013, 803-828.
19. NIBS, FEMA. *Multi-Hazard Loss Estimation Methodology*. Earthquake Model, HAZUS® MH Technical Manual, National Institute of Building Sciences and Federal Emergency Management Agency: Washington DC, 2003 (Last update: 2007); 690.
20. Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S. and Field, N., 2014. *Documentation for the 2014 update of the United States national seismic hazard maps* (No. 2014-1091). US Geological Survey.
21. Prasad, G. G. *Analysis of Bridge Performance Under the Combined Effect of Earthquake and Flood-induced Scour* (Doctoral dissertation, The Pennsylvania State University), 2011.
22. Gordin, E. Performance-based decision-making in post-earthquake highway bridge repair. PhD dissertation. University of California, Berkeley, 2010.
23. Shinozuka, M., Murachi, Y., Dong, X., Zhou, Y., & Orlikowski, M. J. Seismic performance of highway transportation networks. In Proceedings of *China-US Workshop on protection of urban infrastructure and public buildings against earthquakes and man-made disasters*. 2003.
24. Burton, H. V, Deierlein, G., Lallemant, D. & Lin, T. Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience. *Journal of Structural Engineering*. 1–11. 2015. DOI: 10.1061/(ASCE)ST.1943-541X.0001321.
25. Venkittaraman, A., & Banerjee, S. Enhancing resilience of highway bridges through seismic retrofit. *Earthquake Engineering & Structural Dynamics*, *43*(8), 2014, 1173-1191.

26. Caltrans. Historic Bridge Inventory, Sample Plans of Actions. Division of Maintenance, Structure Maintenance. 2005. Accessed url: http://www.dot.ca.gov/hq/structur/strmaint/poa_samp.pdf.
27. Caltrans. City of Rancho Santa Margarita, CA - Bridge Preventative Maintenance Plan. PM00035. 2013. Accessed url: http://www.dot.ca.gov/hq/LocalPrograms/hbrr99/2013/PM00035.pdf.
28. LuAnn Copeland. *User`s manual for QYEWZ-98*. Texas Transportation Institute. The Texas A&M University System. College Station, Texas, 1998.
29. Caltrans. Annual Average Daily Truck Traffic on the California State Highway System. Traffic Data Branch. 2014.
30. Bocchini, P., and D. M. Frangopol. Optimal resilience-and cost-based postdisaster intervention prioritization for bridges along a highway segment. *Journal of Bridge Engineering* 17, no. 1, 2010, pp. 117-129.
31. Kliesen, K. L. *The Economics of Natural Disasters*. Federal Reserve Bank of St. Louis. 1994.
32. Porter, K., Shoaf, K., & Seligson, H. Value of injuries in the Northridge earthquake. *Earthquake Spectra*, *22*(2), 2006, 555-563.
33. Caltrans. High Occupancy Vehicle Lanes Status Report. Sacramento Metropolitan Area. District 3. Office of Freeway Operations, Sacramento. 2011.
34. Gallivan, F., Ang-Olson, J., Papson, A., and Venner, M. *Greenhouse gas mitigation measures for transportation construction, maintenance, and operations activities*, AASHTO Standing Committee on the Environment, San Francisco, 2010.
35. Kendall, A., Keoleian, G. A., & Helfand, G. E. Integrated life-cycle assessment and life-cycle cost analysis model for concrete bridge deck applications. *Journal of Infrastructure Systems*, *14*(3), 2008, 214-222.
36. Zegeer, J., Blogg M, Nguyen K, Vandehey M. Default values for highway capacity and level-of-service analyses. *Transportation Research Record: Journal of the Transportation Research Board* 2071, 2008, 35-43.
37. Beck JL, Porter KA, Shaikhutdinov RV, Au SK, Mizukoshi K, Miyamura M et al. *Impact of seismic risk on lifetime property values.* Monograph, Technical Report: CaltechEERL:2002. EERL-2002-04, California Institute of Technology, 2002.