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RESEARCH ARTICLE-CIVIL ENGINEERING

Probabilistic Seismic Resilience-Based Cost–Benefit Analysis for Bridge Retrofit Assessment

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Abstract

This paper explores a probabilistic resilience-based cost–benefit model that can be used to identify the best retrofit measures for bridges. In the model, the increase in resilience is considered to be the benefit of seismic retrofit. A bridge functionality assessment model is also proposed to evaluate resilience. The functionality is estimated based on the appropriate seismic loss and exponential recovery function models. Then, the functionality assessment model is validated with the field data of the post-earthquake recovery process of bridges. The whole proposed methodology is applied to a non-seismically designed multi-span simply supported concrete girder bridge located in Charleston. Seven retrofit measures, including steel jackets, seat extenders and elastomeric isolation bearings, are applied to the as-built bridge in order to assess their cost-effectiveness. The results show that the cost-effectiveness of retrofit measures varies with the ground motion intensity, and the best retrofit is seat extenders followed by elastomeric isolation bearings when considering the seismic hazard of Charleston. Sensitivity analysis is also performed to identify major uncertain parameters to which the resilience-based cost–benefit ratios are most sensitive. Statistical analysis of resilience-based cost–benefit ratios obtained through random sampling of major uncertain parameters reveals that normal distribution can be used to describe their uncertain nature. The 90% confidence intervals of resilience-based cost–benefit ratios estimated from random sampling also indicate the high cost-effectiveness of seat extenders and elastomeric isolation bearings to enhance bridge performance.

Keywords Seismic resilience · Cost–benefit · Bridges · Seismic retrofit · Functionality

1 Introduction

Bridges have been found to be a very vulnerable component in past earthquakes such as Tangshan, Wenchuan and Central Italy [1–3]. As a key element of transportation networks, the damage of highway bridges due to seismic events may lead to severe disruption of the transportation networks and cause undesirable changes in the technical, organizational, societal and economic conditions of a community. In addition to direct losses (e.g., bridge repair costs), the earthquake-induced bridge damage also results in indirect losses that are associated with the increased travel time and distance, business interruption, revenue and among others. To reduce such consequences, seismic retrofits can be applied to the bridge. Available retrofit measures include steel or RC jackets [4–6], isolation bearings [7, 8], restrainer cables [9, 10], seat extenders [11] and buckling-restrained braces [12]. While these retrofit measures can be available in some regions, questions remain as to the most cost-effective retrofit measure and a method for their assessment and selection.

To address these problems, the methods based on cost–benefit analysis can be used. These methods are very useful to identify the most cost-effective retrofit strategy for structures subjected to extreme natural events. For example, Mondoro and Frangopol [13] emphasized the use of benefit–cost analysis for individual management strategies to determine the cost-effective retrofit for the case study bridge under the river flows expected for the three flood hazard exposure cases. Dong and Frangopol [14] also underlined the use of probabilistic cost–benefit analysis to support the flood hazard mitigation procedure of portfolios of buildings under different retrofit actions in a life-cycle context. In addition to the methods associated with cost–benefit

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analysis, Vitiello et al. [15] proposed a simplified method based on a semi-probabilistic methodology to identify the most cost-effective retrofit strategy and strengthening levels for existing structures during their structural lifetime. However, their optimal retrofit strategies have typically been established in spite of the considerations for the influences of reduced failure probabilities of structures, reduced negative consequences due to failures (e.g., negative socioeconomic consequences) and reduced recovery time from the disaster on benefits of upgrades; they have only considered economic dimension (e.g., life-cycle costs, discounted expected losses). Therefore, it is obvious that the existing methods for identifying the optimal retrofit strategies for structures vulnerable to extreme natural events have failed to capture the integrated benefits of retrofits.

Recently, disaster resilience has gained increasing attention from researchers [16–20]. Pertaining to the seismic resilience of bridges, Venkittaraman and Banerjee [21] stated that seismic resilience of highway bridges could be represented as an integrated measure of bridge seismic performance, expected losses and recovery after the occurrence of seismic events. The calculation of bridge resilience before and after the application of the retrofit strategy not only indicated the effectiveness of this strategy in improving bridge seismic performance but also exhibited the impact of retrofit on system functionality under regional seismic hazard. More recently, Gidaris et al. [22] demonstrated that the comprehensive resilience assessment methodology for bridge portfolios subjected to various hazards facilitated pre-event and post-event mitigation and optimized emergency response strategies of transportation systems as well. Based on these studies, it can be concluded that resilience is not only a comprehensive measure for assessing bridge seismic performance but also a critical basis of a decision-making tool for pre-event and post-event risk management. Besides, the increase in resilience due to seismic upgrades considers the influence of the following important benefits, such as reduced failure probabilities of structures, alleviation of negative consequences because of failures (e.g., socioeconomic consequences) and fast recovery after extreme natural events. Thus, the benefit of the seismic upgrade is represented by the increase in bridge resilience in the present study.

Although the framework for the optimal resilience- and cost-based prioritization of interventions on bridges was proposed by Bocchini and Frangopol [23], they did not account for which retrofit was the most cost-effective. The paper aims to propose a resilience-based cost–benefit analysis (RBCBA) model that addresses the trade-off of enhancement of resilience and retrofit costs corresponding to seven different retrofit measures, including steel jackets, elastomeric isolation bearings and combination of shear keys and restrainer cables. Based on this model, the most cost-effective retrofit strategy of the bridge can be identified. To illustrate the application of the proposed model, a highway bridge located in Charleston, South Carolina is taken as the test-bed [24]. Since the post-event recovery processes of bridges are complicated due to their dependencies on availability of local resources, the leadership of the local government, and preparedness response to the events, it is often difficult to develop the recovery models. To this end, a new bridge functionality assessment model, which is validated with the field data of the post-earthquake recovery process of the highway bridge in China [25], is proposed. The resilience of as-built and retrofitted bridges can be evaluated based on the functionality analysis model and control times of interest. Based on the increase in resilience due to retrofits and associated costs, the resilience-based cost–benefit ratios (RBCBRs) are assessed, which provides new insight into the most cost-effective retrofit strategy. To investigate input uncertain parameters to which the RBCBRs are most sensitive, sensitivity analysis is performed. After the identification of major uncertain parameters, the Latin Hypercube technique is used for random sampling. The statistical analysis of the RBCBRs obtained through random sampling of these major parameters is performed. Then, the 90% confidence intervals of RBCBRs are estimated, which can also provide insight into viable retrofit measures. The methodology proposed herein can be extended to identify the optimal retrofits for other engineering structures, lifeline networks, or communities and be embedded in the comprehensive risk management framework.

2 Framework for Identification of Optimal Retrofit for Bridge

Seismic resilience is an integrated measure for assessing bridge seismic performance [26, 27]. As can be seen from past studies [21, 28], retrofits can enhance the seismic resilience of bridges. However, upgrade actions of bridges mentioned above are performed with the assumption that local resources are abundant. In practice, resources are often limited, which may impede the application of some retrofit strategies. Furthermore, different bridges should be retrofitted with different measures. Therefore, it is necessary to identify the most cost-effective retrofit strategy for a specified bridge. Although the methods based on cost–benefit analysis are widely used in the assessment and selection of retrofit measures, they fail to capture complete benefits of retrofits. To assess comprehensive benefit of retrofit, seismic resilience is used. Then, the RBCBA model, which integrates the retrofit costs and bridge resilience, is proposed. As a comprehensive decision-making methodology, it can be used to select the optimal retrofit measure for the bridge.

The framework for identifying the best retrofit strategy for the bridge is outlined in Fig. 1.

2.1 Probabilistic Resilience-Based Cost–Benefit Analysis

The ratios of resilience differences between retrofitted and as-built bridges to retrofit costs are used for the RBCBA of retrofit measures in general. The retrofit measure with the largest ratio shows that limited resources can be fully utilized to obtain the most benefits, namely this is the most cost-effective retrofit strategy. As mentioned above, the benefit of retrofit can be substituted by the increase in resilience, thus the RBCBRs can be estimated by the following equation:

$$\begin{aligned}\mathrm{RBCBR}_{R,C}(IM,l) &= \frac{R_l(IM)-R_0(IM)}{\frac{C_l}{C_0}-1}\\ &= \frac{C_0\times\left(R_l(IM)-R_0(IM)\right)}{RC_l}\\ &= \frac{R_l(IM)-R_0(IM)}{r_l}\end{aligned} \tag{1}$$

where IM is the intensity measure (e.g., peak ground acceleration (PGA)), R_l and C_l represent the seismic resilience and the total cost of the retrofitted bridge using the retrofit strategy l, respectively, R_0 and C_0 are the seismic resilience and the total cost of the as-built bridge, respectively; RC_l is the retrofit cost of the strategy l; r_l is the retrofit cost ratio, which can be estimated by Eq. (17). The detailed seismic resilience assessment can be found in Sect. 2.2. The total cost of the as-built bridge can be evaluated by multiplying the deck surface area and cost per square feet. The total costs of retrofitted bridges are equal to the sum of retrofit costs and the total cost of the as-built bridge.

From a mathematical perspective, Eq. (1) may lead to biased estimation of RBCBRs when the retrofit costs are low enough. However, this consideration may be unnecessary because the retrofit costs are usually large enough to make sure of the unbiased estimation in the practical application. For example, the retrofit strategy with the lowest cost is restrainer cables, and the cost of each restrainer cable is $634 in 2019 [29]. Besides, the labor costs should also be considered in the estimation of retrofit costs. Thus, Eq. (1) can perform the unbiased estimation of RBCBRs. Similar methods can be found in past studies [13, 21, 30].

2.2 Seismic Resilience

Resilience research has gained much attention in recent years. After the development of the conceptualization framework for resilience, the emphasis has been put on the methods for resilience quantification. Several methods for resilience quantification of a single structure or system have been proposed by some researchers [31–35]. Although community resilience is even more significant from a social perspective, the resilience of a single structure, which paves the way for the community resilience research, is also important. To quantify the seismic resilience of a single bridge, the following equation is used [36]:

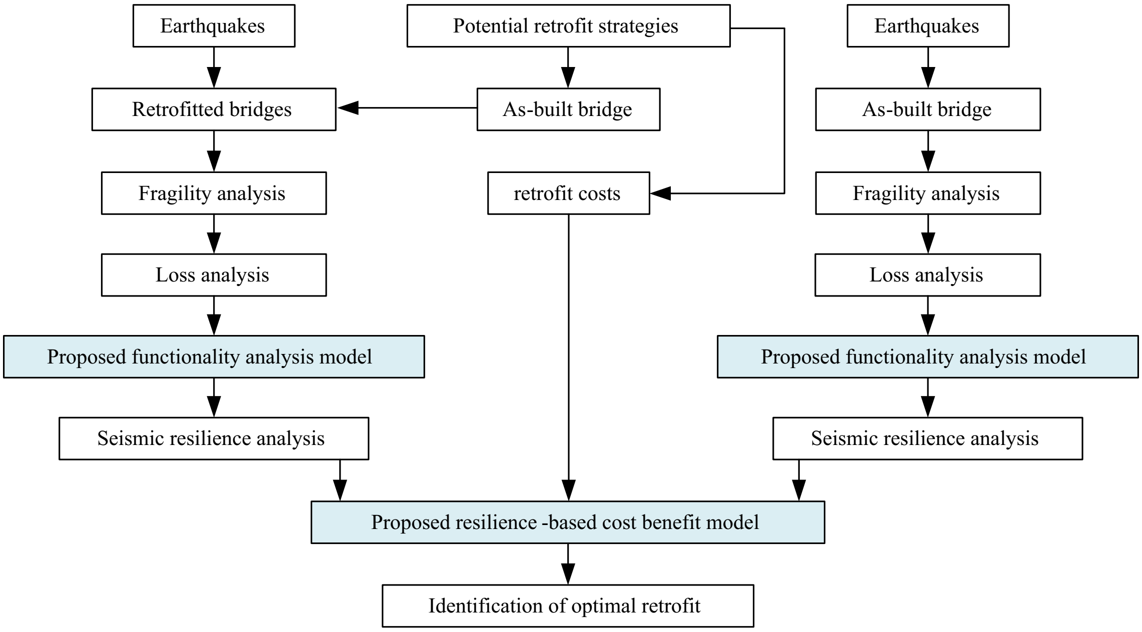


Fig. 1 Framework for identification of optimal retrofit strategy for bridge

$$R = \frac{\int_{t_\mathrm{o}}^{t_\mathrm{o}+t_\mathrm{h}} Q(t)\mathrm{d}t}{t_\mathrm{h}} \tag{2}$$

where t_o is the occurrence time of the seismic event; t_h is the time horizon of interest (e.g., life-cycle of bridge), and $Q(t)$ is the functionality of the bridge. Figure 2 is used to describe the functionality $Q(t)$ over time. As shown in the figure, the functionality of bridge maintains 100% before earthquakes, and it immediately drops to a certain level when an earthquake occurs at time t_o. The residual functionality $Q\left(t_\mathrm{o}\right)$ can be described as robustness. If three different restoration strategies can be applied to the bridge, three different recovery paths with different recovery times can be obtained. According to restoration strategies, the bridge functionality after restoration may be higher or lower than or equal to the initial functionality. The robustness and rapidity related to bridge resilience are also shown in Fig. 2.

2.2.1 Functionality Assessment Model

To evaluate bridge resilience, the functionality should be estimated first. The analytical expression of functionality in this paper considers the contribution of two components. Each functionality component is estimated based on seismic loss and recovery models. More specifically, the following equations are used to assess bridge functionality $Q(t)$:

$$Q(t) = \gamma\left(\alpha(t)Q_1(t) + \beta(t)Q_2(t)\right) \tag{3}$$

$$\begin{aligned} Q_1(t) = Q\left(t_\mathrm{o}\right) + \left[H\left(t - t_\mathrm{o}\right) - H\left(t - \left(t_\mathrm{o} + T_\mathrm{R}\right)\right)\right] \\ \times f_{\mathrm{rec},1}\left(t, t_\mathrm{o}, T_\mathrm{R}\right) \times \left(Q_\mathrm{ex}(T_\mathrm{R}) - Q\left(t_\mathrm{o}\right)\right) \end{aligned} \tag{4}$$

$$\begin{aligned} Q_2(t) = Q\left(t_\mathrm{o}\right) + \left[H\left(t - t_\mathrm{o}\right) - H\left(t - \left(t_\mathrm{o} + T_\mathrm{R}\right)\right)\right] \\ \times f_{\mathrm{rec},2}\left(t, t_\mathrm{o}, T_\mathrm{R}\right) \times \left(Q_\mathrm{ex}(T_\mathrm{R}) - Q\left(t_\mathrm{o}\right)\right) \end{aligned} \tag{5}$$

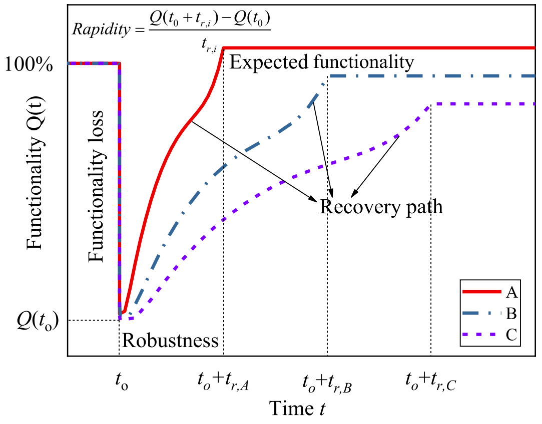


Fig. 2 Schematic representation of bridge resilience

$$\alpha(t) = \frac{Q_1^3(t)}{\sum_{i=1}^{2} Q_i^3(t)} \tag{6}$$

$$\beta(t) = \frac{Q_2^3(t)}{\sum_{i=1}^{2} Q_i^3(t)} \tag{7}$$

$$Q\left(t_o\right) = 1 - L\left(I, T_\mathrm{R}\right) \tag{8}$$

where $Q_1(t)$ and $Q_2(t)$ are the two functionality components; $Q\left(t_\mathrm{o}\right)$ represents the residual functionality; $\alpha(t)$ and $\beta(t)$ are the weight factors; γ is the correction coefficient; t_o and T_R represent the occurrence time of the seismic event and the recovery time of the bridge, respectively; $H()$ is the Heaviside step function, and the value of zero is obtained when $t \le t_\mathrm{o}$ or $t_\mathrm{o} + T_\mathrm{R} \le t$; $f_{\mathrm{rec},1}\left(t, t_\mathrm{o}, T_\mathrm{R}\right)$ and $f_{\mathrm{rec},2}\left(t, t_\mathrm{o}, T_\mathrm{R}\right)$ are the two recovery models; I represents the seismic intensity; $L\left(I, T_\mathrm{R}\right)$ represents the loss model, which contains direct and indirect economic losses.

2.2.2 Fragility Analysis

To evaluate bridge functionality, the fragility analysis should be performed. To study the vulnerability of the bridge (system), the component fragility curves should be established. For a certain class of structures, the probabilistic seismic demand models (PSDMs) are used to develop the relationship between ground motion intensity and seismic demands. Optimal intensity measures can be selected based on their efficiency, practicality, sufficiency and hazard computability. As stated by Padgett et al. [37], PGA and spectral acceleration are the most commonly adopted intensity measures in the bridge engineering community. The hazard levels considered in the present study are described in terms of PGA, as shown in Sect. 3.1.3. The field data of the post-earthquake recovery process of highway bridges, which is used to validate the proposed functionality assessment model, are also collected based on PGA. Thus, PGA is used as the intensity measure in the present study. Based on the PSDMs, the component fragility curves can be developed. Using capacities and joint probabilistic seismic demand models of components, the system fragility is developed using the Monte Carlo simulation [38, 39]. The framework for developing the bridge system fragility is shown in Fig. 3, and more details can be found in Nielson [40].

2.2.3 Loss Function Model

The earthquake-induced economic loss can be classified into direct and indirect losses. The direct loss includes repair costs of damaged components, removal costs of debris and construction cost of a temporary bypass. It should be noted that the direct loss assessment of bridge during seismic events is very complicated, and the detailed information, which can be found in Decò et al. [41], is beyond the scope of the present study. For simplicity, damage ratios at slight, moderate, extensive and complete damage states are used to assess direct loss [21, 30]. For a single bridge, the simplified evaluation of direct loss can be given as:

$$L_{\mathrm{d}}(I) = \sum_{k=1}^{n} P(DS = k) \times DR_k \tag{9}$$

where $P(DS = k)$ represents the probability of bridge failure at damage state k; DR_k is the damage ratio corresponding to damage state k. Values of $P(DS = k)$ can be obtained from bridge fragility analysis. As recommended in HAZUS [42], the damage ratios for minor, moderate, extensive and complete damage of bridge are 0.03, 0.08, 0.25 and 2/span number, respectively.

The travel time and distance may be increased due to the bridge damage during seismic events, which can result in indirect loss. The indirect loss consists of many aspects, including business interruption, relocation and traffic delay [21]. Compared with direct loss, the estimation of indirect loss may be more complicated. To consider the losses associated with additional travel time and distance, a simplified method can be used [43]. In this method, the additional travel distance can be converted to running costs $\left(C_{\mathrm{ind,1}}\right)$, which can be given as:

$$C_{\mathrm{ind,1}}\left(I, T_{\mathrm{R}}\right) = C_{\mathrm{RV}} L_{\mathrm{D}} A T_{\mathrm{R}}(I) \tag{10}$$

where C_{RV} is the running vehicle cost; L_{D} is the length of the detour, namely additional travel distance; A represents the average daily traffic (ADT); $T_{\mathrm{R}}(I)$ is the recovery time of the bridge. For the additional travel time, time losses $\left(C_{\mathrm{ind,2}}\right)$ are estimated by [43]:

$$C_{\mathrm{ind,2}}(I, T_{\mathrm{R}}) = \left[C_{\mathrm{A}} O\left(1 - T_{\mathrm{T}}\%\right) + T_{\mathrm{T}}\% C_{\mathrm{truck}}\right] \frac{L_{\mathrm{D}} A T_{\mathrm{R}}(I)}{S} \tag{11}$$

where C_{A} is the time value per adult; O is the occupancy rate; T_{T} represents the percentage of the average daily truck traffic in the ADT; C_{truck} is the time value for truck; S is the average travel speed in detour. To facilitate assessment of total loss caused by earthquakes, the indirect loss $\left(L_{\mathrm{ind}}\left(I, T_{\mathrm{R}}\right)\right)$ can be expressed in the following form:

$$L_{\mathrm{ind}}\left(I, T_{\mathrm{R}}\right) = \frac{C_{\mathrm{ind,1}} + C_{\mathrm{ind,2}}}{C_{\mathrm{replacement}}} \tag{12}$$

where $C_{\mathrm{replacement}}$ is the replacement cost of the bridge. The total loss $\left(L\left(I, T_{\mathrm{R}}\right)\right)$ is given as:

$$L\left(I, T_R\right) = \frac{\left(1 + r\left(I, T_{\mathrm{R}}\right)\right) L_{\mathrm{d}}(I)}{1 + r\left(I, T_{\mathrm{R}}\right) L_{\mathrm{d}}(I)} \tag{13}$$

$$r(I, T_{\mathrm{R}}) = \frac{L_{\mathrm{ind}}\left(I, T_{\mathrm{R}}\right)}{L_{\mathrm{d}}(I)} \tag{14}$$

where $r\left(I, T_{\mathrm{R}}\right)$ represents the ratio of indirect to direct loss.

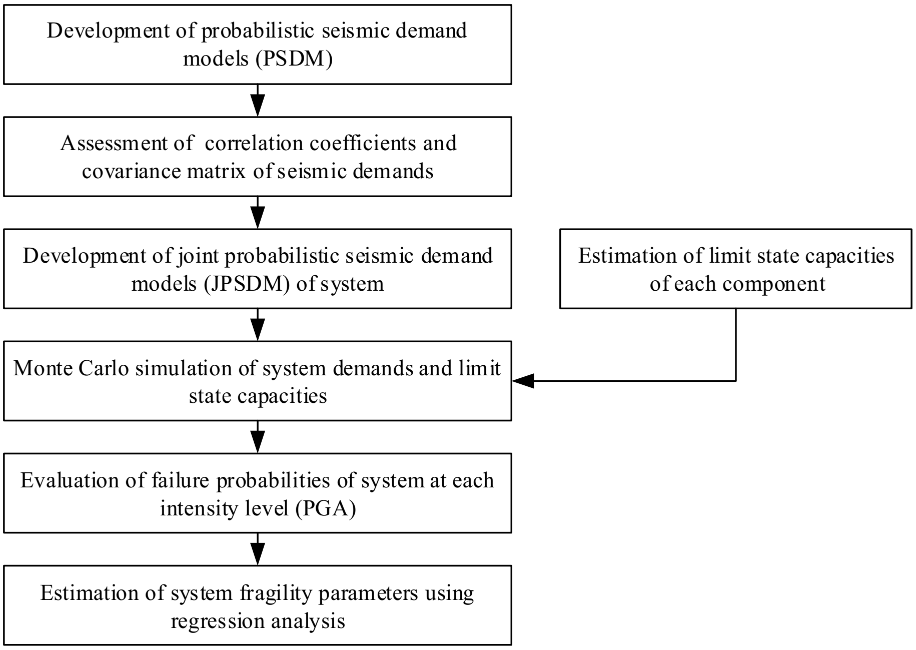


Fig. 3 Framework for evaluating seismic fragility of bridge (system)

2.2.4 Recovery Function Model

Several recovery events, including expeditious recovery to better than old, are suggested by Ayyub [44]. Since many complex factors can impact the recovery process, the recovery models for bridge are extremely difficult to develop. Note that the recovery events mentioned above are just used for simple illustration, and the detailed functions for describing the recovery process are very scarce. Thus, the development of recovery function is imperative. The six-parameter recovery function of the bridge suggested by Decò et al. [41] can be used for this purpose, and the recovery patterns can be classified according to the damage levels and restoration options. Additionally, according to analytical type and available data, the recovery models can be divided into empirical and analytical recovery models [45]. The empirical recovery models are developed with field data interpretation and engineering judgment. For example, the resilience of the Canterbury hospital during the 2011 Christchurch earthquake has been discussed by Jacques et al. [46] with field data, and the functionality of hospital services is evaluated using the fault-tree analysis. For the analytical recovery models, the two exponential recovery functions, which can be used to estimate bridge functionality, are given as:

$$f_{\mathrm{rec},1}\left(t,t_{\mathrm{o}},T_{\mathrm{R}}\right)=e^{-\lambda\left(1-\frac{(t-t_{\mathrm{o}})}{T_{\mathrm{R}}}\right)} \tag{15}$$

$$f_{\mathrm{rec},2}\left(t,t_{\mathrm{o}},T_{\mathrm{R}}\right)=1-e^{-\lambda\left(\frac{(t-t_{\mathrm{o}})}{T_{\mathrm{R}}}\right)} \tag{16}$$

where λ is the constant, which can be assessed when recovery data are available; t_{o} and T_{R} are the occurrence time and the recovery time, respectively.

2.3 Validation of Functionality Assessment Model

Although the functionality assessment model has been established, question remains as to its validation. Since the parameter λ in the recovery models can significantly influence the functionality assessment, the estimation of this parameter is imperative. The data regarding the post-event recovery of the bridge are limited, and the recovery processes used for the development of recovery functions are often oversimplified. To this end, the field data of the post-earthquake recovery process of highway bridges in China are used [25]. In this section, the data concerning the medium bridges, which have total lengths of 30 ~ 100 m, are used to test the proposed model. More specifically, the bilinear recovery model is suggested by Sun and Zou [25], and recovery paths corresponding to each seismic intensity level are shown in Fig. 4. With available recovery data of bridge, the seismic resilience corresponding to each seismic intensity level can be assessed by Eq. (2). It is assumed that the same resilience is obtained based on the proposed functionality assessment model, then the parameter λ in the recovery model can be estimated. Therefore, the applicability of the proposed functionality assessment model is validated. According to the seismic ground motion parameters zonation map of China (2015) [47], each seismic intensity level matches a certain range of peak ground accelerations, as shown in Table 1. Additionally, the parameter λ and correction coefficient γ related to functionality corresponding to each seismic intensity level are also listed in Table 1.

2.4 Assessment of Recovery Time

The rapidity of bridge recovery is influenced by many factors, such as the damage levels and availability of local resources. Since different damage levels of the bridge require different recovery times, it is beneficial to assume recovery times for each damage state. As recommended in the seismic loss estimation manual [48], the recovery times for different damage states of the bridge follow the normal distribution. The mean and standard deviation values of recovery times for each damage state are given in Table 2. To assess the recovery times of bridges, the mean recovery times are used in the present study.

2.5 Retrofit Cost

The retrofit costs vary with retrofit strategies. The retrofit costs are influenced by many factors, such as the prices of raw materials and the labor cost. To simply assess the replacement cost, the deck surface area and cost per square feet can be used. Based on the retrofit practice, the retrofit costs can be evaluated. To facilitate the assessment of RBCBRs, the following equations can be used:

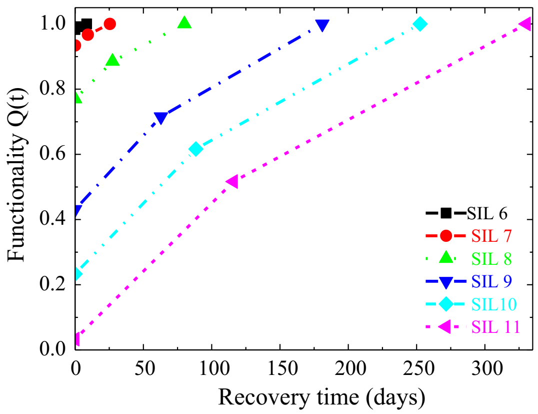


Fig. 4 Recovery processes of highway bridges corresponding to different seismic intensity levels (SIL) [25]

Table 1 Parameters corresponding to each seismic intensity level

PGA	0.04 g ≤ PGA < 0.09 g	0.09 g ≤ PGA < 0.19 g	0.19 g ≤ PGA < 0.38 g	0.38 g ≤ PGA < 0.75 g	0.75 g ≤ PGA
SIL	6	7	8	9	≥10
λ	4.948	4.948	4.947	2.8	2.363
γ	1.0	1.0	1.0	1.024	1.04

PGA peak ground acceleration, *SIL* seismic intensity level

Table 2 Means and standard deviations of post-event recovery times for highway bridges [48]

Damage state	Minor	Moderate	Extensive	Complete
Mean (days)	0.6	2.5	75	230
Standard deviation (days)	0.6	2.7	42	110

$$r_l = \frac{RC_l}{C_0}$$
$$C_l = RC_l + C_0 = C_0(1 + r_l) \tag{17}$$

where r_l is the ratio of retrofit cost of strategy l to replacement cost of as-built bridge; RC_l is the retrofit cost of strategy l; C_0 and C_l represent the replacement costs of as-built and retrofitted bridges, respectively.

3 Case Study

The whole framework for seismic RBCBA proposed above is applied to retrofit assessment of non-seismically multi-span simply supported concrete girder bridge located in Charleston, South Carolina. This bridge has three spans with a total length of 48.8 m. This type of bridge is widely used in the transportation network owing to its simple structure and easy construction. However, they may be vulnerable to earthquakes because of large longitudinal deformations, span unseating and among others. To enhance the seismic performance of the bridge, seismic retrofit strategies, including steel jackets, restrainer cables and elastomeric isolation bearings are used. Since the resources are often limited, it is necessary to identify the most cost-effective retrofit measure. Based on the RBCBA model proposed in the present study, the most cost-effective retrofit measure can be identified, which provides new insight into suggestions concerning risk-wise investment.

Table 3 List of abbreviations

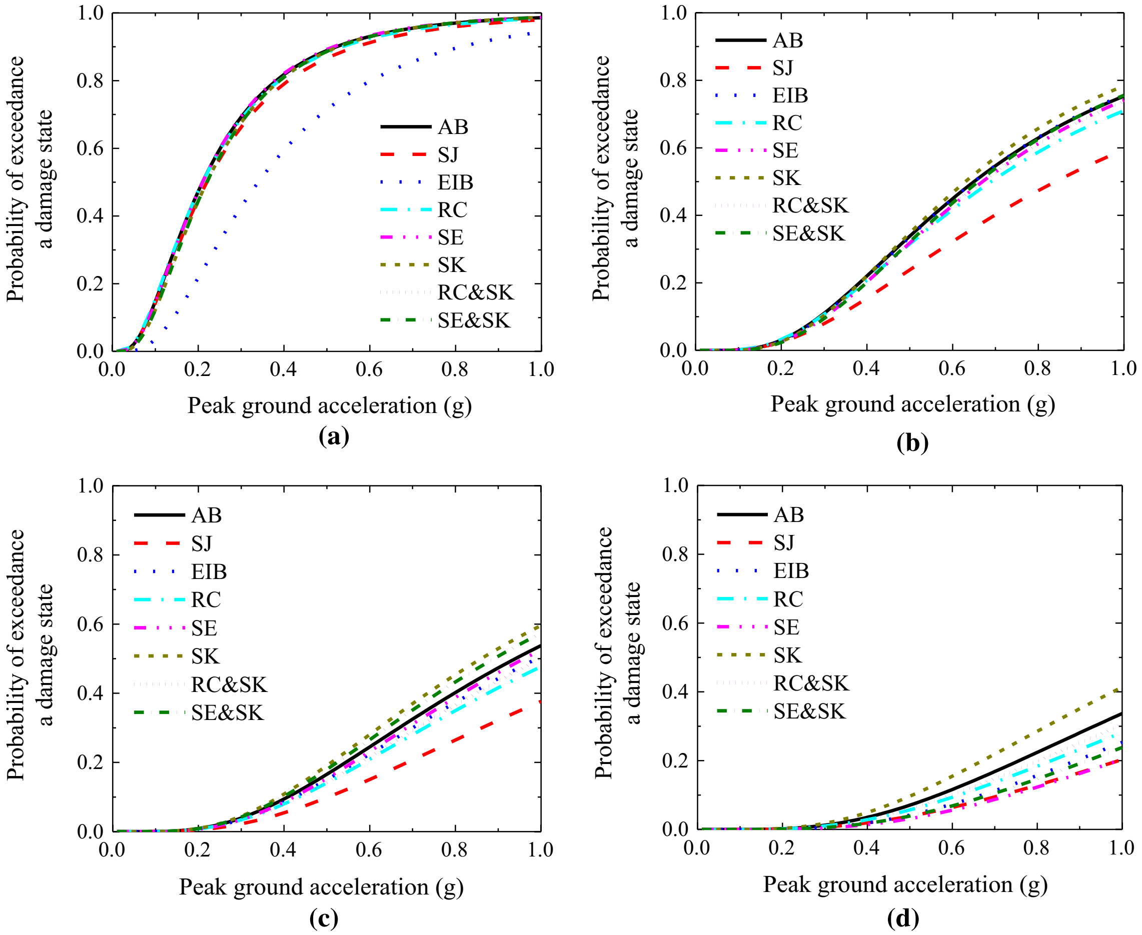
Element	abbreviations
As-built	AB
Steel jackets	SJ
Elastomeric isolation bearings	EIB
Restrainer cables	RC
Seat extenders	SE
Shear keys	SK
Restrainer cables and shear keys	RC&SK
Seat extenders and shear keys	SE&SK

3.1 Seismic Resilience Analysis

To assess the resilience of bridges, the proposed functionality assessment model is used. This model considers the contribution of two functionality components. The seismic losses and recovery paths should be determined to assess functionality components. The seismic losses, which consist of direct and indirect losses, can be estimated based on fragility analysis, time losses and running costs. Two available recovery models are used to describe the post-event recovery processes of bridges. For simplified and convenient reference, the abbreviations of the seven retrofit strategies are used, as shown in Table 3.

3.1.1 Seismic Loss Analysis

The fragility curves of as-built and retrofitted bridges, which have been developed by Padgett [24], are shown in Fig. 5. Based on the damage ratios and the bridge failure probabilities at each damage state, the direct losses of bridges under seismic events can be estimated. The parameters that are used to assess indirect losses are listed in Table 4. Then the indirect losses of bridges are assessed, and the ratios of indirect to direct losses are shown in Fig. 6. As can be seen, the indirect losses are about 6 ~ 80 times larger than direct losses, and these ratios increase with the increase in ground motion intensity levels. Note that the direct and indirect losses are estimated based on the fragility analysis, and the fragility functions take the form of lognormal cumulative



(a) (b) (c) (d)

Fig. 5 Fragility curves for as-built and retrofitted bridges: **a** minor damage; **b** moderate damage; **c** extensive damage; **d** complete damage [24]

Table 4 Parameters used for indirect loss analysis

Parameters	Value	References
Running vehicle cost C_{RV} (\$/km)	0.16	Stein et al. [43]
Detour length L_D (km)	15	Assumed
Average daily traffic A	15,640	Assumed
Value of time per adult C_A (\$/h)	7.05	Stein et al. [43]
Occupancy rate O	1.56	Stein et al. [43]
Percentage of average daily truck traffic T_T	4%	Stein et al. [43]
Time value for truck C_{truck} (\$/h)	20.56	Stein et al. [43]
Average travel speed in detour S (km/h)	64	Stein et al. [43]

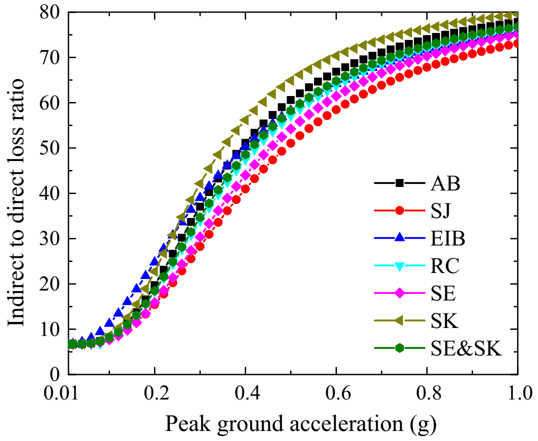


Fig. 6 Ratios of indirect to direct losses

distribution functions. Thus, the peak ground acceleration (PGA) must be larger than zero. The figure indicates that the smallest ratio of indirect-to-direct loss is equal to 6 when PGA = 0.01 g. Additionally, the direct and indirect losses of bridges are caused by earthquakes (PGA > 0), and the indirect-to-direct loss ratio has no significance when PGA = 0 (namely there is no earthquake).

3.1.2 Initial Functionality Losses and Recovery Times

For the present case study, the expected functionality of bridges is assumed to be 1. The initial functionality losses of bridges are estimated at the time immediately after an earthquake $\left(t = t_o\right)$. According to Eqs. (3)–(8), the initial functionality losses can be evaluated. However, there is no need to assess the initial functionality losses for all PGAs. Thus, the initial functionality losses for representative PGAs ranging from 0.1 g to 1.0 g with the increment of 0.1 g are estimated (Fig. 7a). According to seismic fragility analyses and recovery times corresponding to each damage state, recovery times of bridges during seismic events can be assessed (Fig. 7b).

3.1.3 Results and Discussion of Seismic Resilience Analysis

After the assessment of seismic losses and recovery times, the functionality of bridges can be assessed by the model proposed in the present study. As discussed previously, two exponential recovery models are used to estimate functionality components. Under the assumption that bridges are restored to their original states and control times are equal

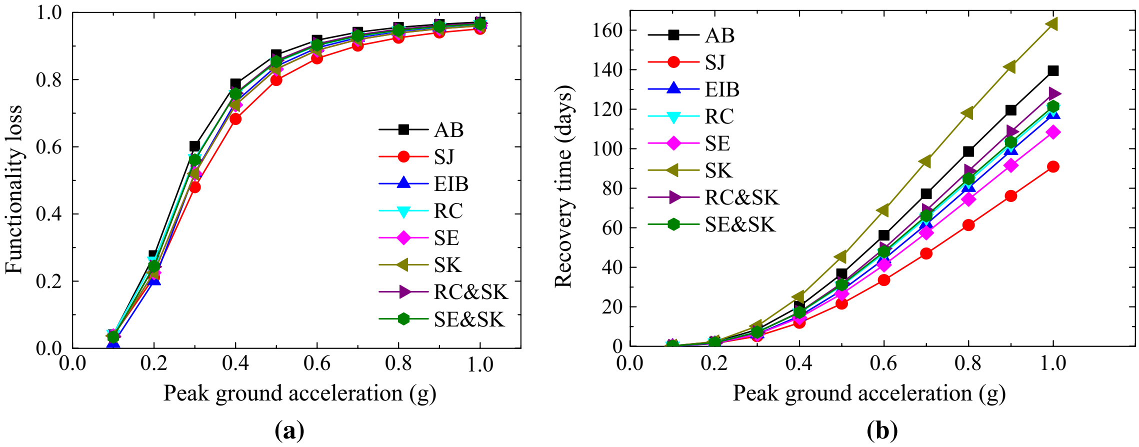


Fig. 7 **a** Initial functionality losses and **b** recovery times for as-built and retrofitted bridges

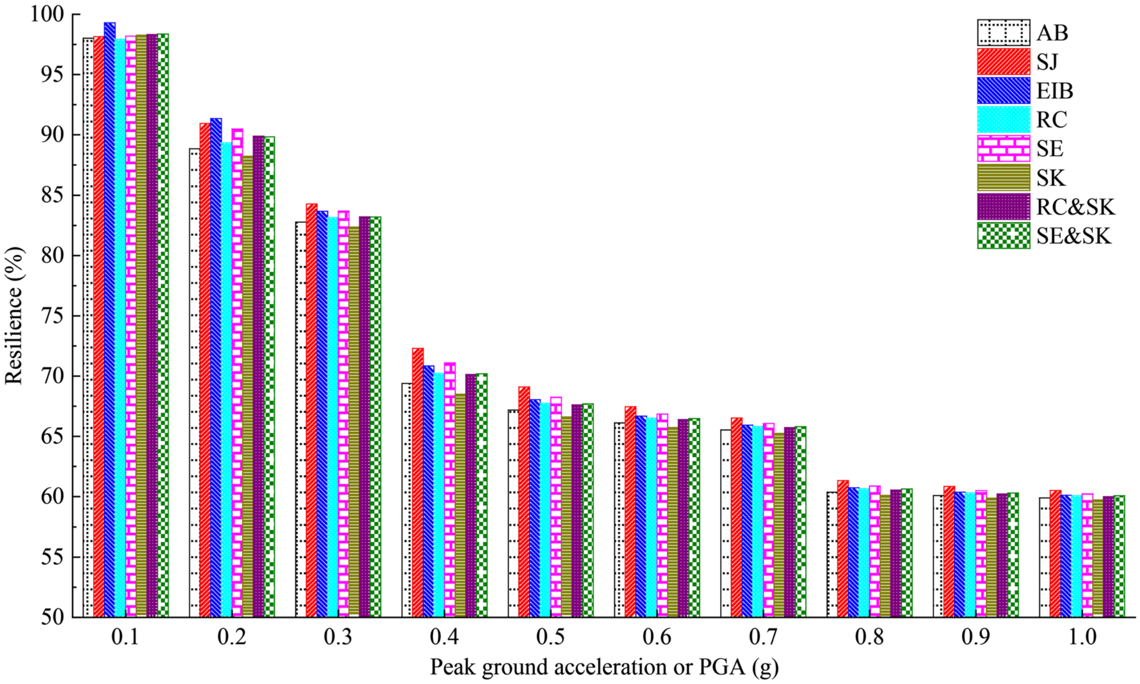


Fig. 8 Seismic resilience of as-built and retrofitted bridges

to their recovery times, seismic resilience of bridges can be estimated by Eq. (2) (Fig. 8).

As can be seen from Fig. 8, all the retrofit strategies can improve the bridge resilience when 0.2 g ≤ PGA ≤ 1.0 g, except for the shear keys. A comparison of resilience of bridges shows that the best retrofit measure varies with ground motion intensities. For example, when PGA = 0.2 g, the bridge with the highest resilience is retrofitted by elastomeric isolation bearings, whereas steel jackets result in the highest resilience when PGA amounts to 0.4 g. This indicates that the best retrofit strategy is related to bridge location (with specific PGA) when only resilience is considered. Moreover, the enhancement of bridge resilience due to retrofits also varies with ground motion intensities. For the steel jackets, seismic resilience increases by 2.4%, 4.2% and 1% with PGAs of 0.2 g, 0.4 g and 1.0 g, respectively. This indicates that the optimal application for a certain retrofit measure should also consider regional seismic hazards.

For the shear keys, seismic resilience is larger than that of the as-built bridge when PGA is small (e.g., PGA = 0.1 g). However, the retrofitted bridge resilience is lower than that of the as-built bridge when 0.2 g ≤ PGA ≤ 1.0 g. This lower resilience can be attributed to the fact that the shear keys can increase bridge vulnerability when transverse excitation is considered. More specifically, past earthquakes have shown that the bearings, abutments and concrete columns are the most vulnerable components, thus the bridge fragility curves are developed by comparing the demand models to capacity estimates for these components. The as-built bridge is multi-span simply supported concrete girder bridge, and the superstructure of this bridge has a large mass, which can lead to large inertial loads when the bridge is excited in the transverse direction. The inertial loads become larger when the stronger ground motions (with larger PGAs) are considered. The shear keys facilitate inertial loads transfer to the columns, which increases the fragilities of bridge columns. Then the bridge fragility is increased due to the increase in columns fragilities. Similar findings of the negative effect of shear keys on the bridge have also been discussed in past studies [13, 24, 49].

For the restrainer cables, seismic resilience is slightly lower than that of the as-built bridge when PGA = 0.1 g. This is because the restrainer cables can increase the vulnerability of abutments and increase the vulnerability of the bridge system at last. The restrainer cables are used to restrain the longitudinal displacement of the bridge deck. As discussed previously, the bridge fragility curves are developed by comparing demand models to capacity estimates for bearings, columns and abutments. Since the abutments are more vulnerable in active action than in passive action, the restrainer cables, which can only transfer the developed seismic force to the abutments in active action, increase the vulnerability of abutments. However, this negative effect of restrainer cables on bridge vulnerability can be neglected when larger peak ground accelerations (0.2 g ≤ PGA ≤ 1.0 g) are considered. This is because the span unseating is of great concern when larger PGAs are considered, and the restrainer cables can reduce the probability of span unseating. Furthermore, the bearings and columns are more vulnerable than abutments when larger PGAs are considered. Similar findings can be found in [13, 50].

It is important to note that the resilience of all bridges drops quickly at first and then continues to decrease slowly. This implies that the impacts of earthquakes on bridges increase slowly when earthquake intensities increase to a certain level. To describe the functionality of bridges over time, functionality curves corresponding to the PGAs of 0.1 g, 0.5 g, and 1.0 g are used (Fig. 9). In the figure, the occurrence time of the earthquake is assumed to be the twentieth day of the bridge life-cycle, and the aging effect is not considered. As shown in the figure, most retrofit measures can enhance the residual functionality and shorten the recovery time of the bridge, which reveals that the robustness and recovery rapidity of the bridge can be improved by the most seismic retrofit measures.

The bridges investigated in the present study are located in Charleston, South Carolina, where the PGAs with exceedance probabilities of 10%, 5% and 2% in 50 years are 0.2453 g, 0.4651 g and 0.8676 g, respectively. To assess the total resilience of bridges, these three hazard

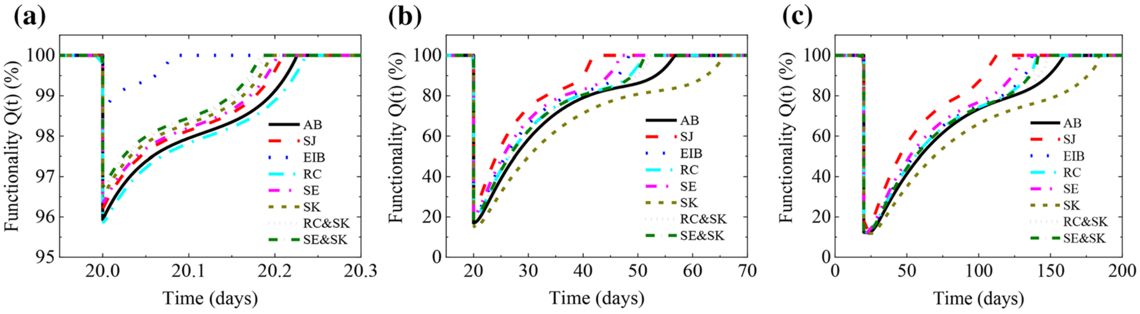


Fig. 9 Functionality of bridges over time for **a** PGA = 0.1 g, **b** PGA = 0.5 g and **c** PGA = 1.0 g

Table 5 Resilience of bridges considering seismic hazard of Charleston

Exceedance probability in 50 years (%)	Resilience (%)							
	AB	SJ	EIB	RC	SE	SK	RC&SK	SE&SK
10	85.03	87.27	86.84	85.53	86.58	84.38	85.87	85.83
5	67.76	69.97	68.78	68.40	69.01	67.10	68.28	68.35
2	60.16	60.97	60.47	60.41	60.60	59.94	60.31	60.39
Total hazard	77.03	79.08	78.42	77.54	78.36	76.42	77.69	77.69

levels are considered. The seismic resilience of all bridges is shown in Table 5. As can be seen, the bridge with the highest resilience is retrofitted by elastomeric isolation bearings, while the lowest resilience is obtained by shear keys. Besides, the effectiveness of the most retrofit measures to enhance the seismic performance of the bridge is further demonstrated.

3.2 Resilience-Based Cost–Benefit Analysis

The resilience is an integrated measure for seismic performance assessment of the bridge. From the analysis above, most of the retrofits can enhance the seismic resilience of the bridge. It should be noted, however, that the retrofit measures mentioned above are applied to the bridge with the assumption that the local resources are abundant. However, the resources for bridge retrofit are often limited, which may impede the application of some retrofit strategies. Therefore, it is necessary to identify the optimal retrofit measure for bridge considering local resources. The RBCBA proposed in the paper can be used for this purpose. As a comprehensive decision-making methodology, it can provide new insight into the most cost-effective retrofit measure for bridges.

3.2.1 Retrofit Costs

The retrofit costs vary with different retrofit strategies, and they are influenced by many factors, such as the prices of raw materials and labor costs. To assess the replacement cost of the as-built bridge, the deck surface area and cost per square feet can be used. The dollar values are converted to 2019 dollars assuming a 6% inflation rate. The replacement cost of multi-span simply supported concrete girder bridge (as-built bridge) is estimated as 483,814 dollars [29]. Based on the retrofit costs suggested by Padgett et al. [29], the steel jackets for each column are estimated to cost 10,137 dollars; the cost of elastomeric isolation bearings is estimated to be 5% of replacement cost of as-built bridge; each restrainer cable is estimated to cost 1191 dollars; the cost of each shear key is equal to that of each seat extender, which is estimated to be 634 dollars. For retrofit costs corresponding to shear keys and seat extenders, the labor cost of 5068 dollars should also be considered. Finally, the ratios of retrofit costs to the replacement cost of the as-built bridge are summarized in Table 6.

Table 6 Retrofit cost ratios

Retrofit strategy	Retrofit cost ratio (%)
AB	0
SJ	12.57
EIB	4.99
RC	3.94
SE	3.14
SK	8.12
RC&SK	12.06
SE&SK	11.26

3.2.2 Benefit of Retrofit

Bridge retrofit helps to reduce the bridge damage and seismic losses. As discussed previously, bridge resilience is not only an integrated measure of bridge seismic performance but also a critical basis of the decision-making tool for pre-event and post-event risk management. Besides, according to Bruneau et al. [51] and Cimellaro et al. [45], resilience can also be measured from four dimensions: technical, organizational, social and economic (TOSE). Technical resilience describes the capacity of systems to withstand natural hazards, for example, assessment of technical resilience should include whether the system can perform to an acceptable level during seismic events. Organizational resilience describes the ability of organizations to manage systems, including whether the emergency services are available and whether the government can make wise decisions for recovery and rebuilding in a short time. Social resilience describes the capacity to reduce functionality loss and minimize the negative consequences caused by disasters. Economic resilience describes the ability to reduce economic loss, including direct and indirect losses. Note that the resilience is an integrated measure for seismic performance assessment of bridge, and enhancement of bridge resilience due to seismic upgrades can consider the influence of the following important benefits, such as reduction in the failure probabilities of structures, alleviation of negative consequences because of failures (e.g., casualty, socioeconomic consequences) and fast recovery after extreme natural events. Therefore, the increase in resilience is used as the benefit of retrofit in the present study.

3.2.3 Results and Discussion of Resilience-Based Cost–Benefit Analysis

Based on the methodology proposed in the previous sections, the RBCBRs for retrofit of bridges can be estimated. The assessment results are listed in Table 7. In the table, the largest ratio in each column shows the most cost-effective retrofit strategy suggested by the RBCBA when a specified PGA is considered. It should be noticed that the optimal retrofit strategy suggested by the RBCBA may be different from that of seismic resilience analysis. For example, although the highest resilience of the bridge is obtained by steel jackets when PGA = 0.4 g, the most cost-effective retrofit measure is seat extenders. This indicates that the influence of retrofit costs should not be neglected when stakeholders make a wise investment.

When the same PGA is considered, weight factors for retrofit strategies can be estimated based on the results from Table 7 (Fig. 10). The larger weight factors indicate the high cost-effectiveness of retrofit measures in the group (available retrofit strategies). For example, the largest weight factor can be obtained by elastomeric isolation bearings when PGA = 0.1 g, which shows that this is the most cost-effective retrofit measure. This advantage can be attributed to their relatively low costs and good energy dissipation capacity. More specifically, these isolation bearings can be regarded as flexible connections between substructure and superstructure of the bridge; thus, seismic energy can be dissipated and the damage to the bridge during seismic events can be reduced. Although the restrainer cables and seat extenders have small weight factors when PGA = 0.1 g, both of their weight factors increase with the increase in PGAs. This indicates that these two retrofit strategies are more cost-effective when larger PGAs are considered. For example, the RBCBR of seat extenders is 0.164 when PGA = 0.8 g, and this is the most cost-effective retrofit strategy followed by steel jackets

Table 7 Resilience-based cost–benefit ratios for retrofit measures

Retrofit strategy	Resilience-based cost–benefit ratio									
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g	0.7 g	0.8 g	0.9 g	1.0 g
AB	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SJ	0.010	0.167	0.119	0.232	0.152	0.106	0.078	0.076	0.060	0.049
EIB	0.255	0.501	0.179	0.290	0.171	0.112	0.079	0.073	0.055	0.044
RC	−0.022	0.124	0.095	0.211	0.142	0.100	0.075	0.072	0.058	0.047
SE	0.055	0.521	0.293	0.543	0.342	0.234	0.171	0.164	0.129	0.105
SK	0.032	−0.076	−0.050	−0.109	−0.070	−0.048	−0.035	−0.033	−0.026	−0.021
RC&SK	0.026	0.087	0.036	0.062	0.036	0.023	0.016	0.014	0.011	0.009
SE&SK	0.031	0.088	0.038	0.072	0.046	0.032	0.024	0.023	0.019	0.015

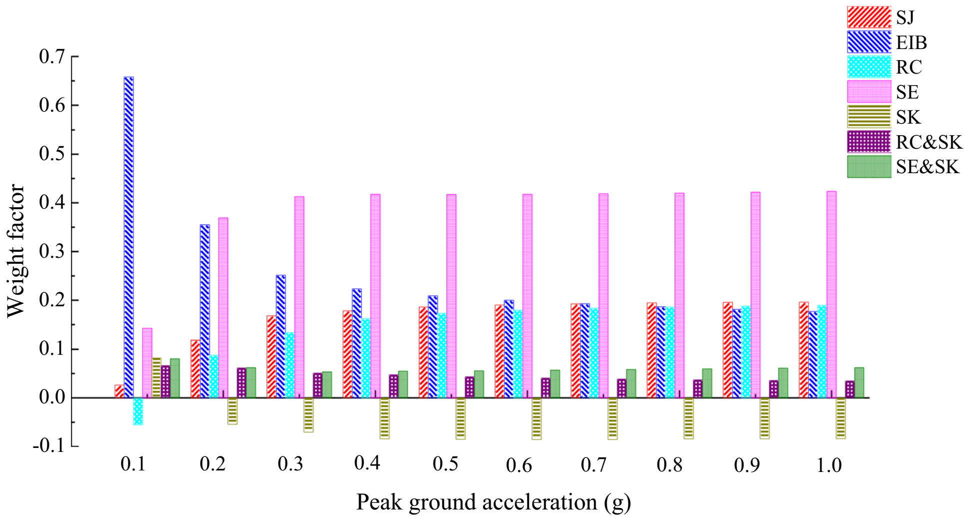


Fig. 10 Weight factors of retrofit strategies

and restrainer cables. These results are consistent with the fact that span unseating is of great concern when large earthquakes (with large PGAs) are considered, and both of them can diminish the longitudinal displacements of bridge spans and reduce the probability of span unseating.

Note that the negative values of RBCBRs for restrainer cables and shear keys are obtained, while the results do not mean that these retrofit strategies are not feasible due to their ability to keep post-event normal traffic. Moreover, the restrainer cables and shear keys can prevent span unseating, and the loss of life avoided, loss of transportation tools (e.g., cars, trucks) avoided and cost of cleaning broken bridge decks avoided have not been considered in the present study, which also constitutes the benefits of retrofits. The shear keys, the combined use of shear keys and restrainer cables or seat extenders have low RBCBRs and weight factors when 0.2 g ≤ PGA ≤ 1.0 g; thus, none of them are the preferred retrofit strategies when alternatives are available.

The small earthquakes (with small PGAs) usually result in slight or moderate damage to the bridge, while the large earthquakes (with large PGAs) often cause extensive or complete damage. A comparison of RBCBRs reveals that the most cost-effective retrofit strategy varies with PGAs. For example, the most cost-effective retrofit strategy is elastomeric isolation bearings when PGA = 0.1 g, while seat extenders are considered as the most cost-effective retrofit measure when 0.2 g ≤ PGA ≤ 1.0 g. For the elastomeric isolation bearings, this can be attributed to their effectiveness at the slight and moderate damage states when small PGAs are considered. For the seat extenders, this can be attributed to their effectiveness at the complete damage state when larger PGAs are considered. The multi-span simply supported concrete girder bridge considered in the present study is located in Charleston, South Carolina and the seismic resilience of bridges considering the local total hazard is shown in Table 5. According to the seismic resilience and retrofit cost ratios from Tables 5 and 6, respectively, the most cost-effective seismic retrofit strategy suggested by RBCBA can be identified (Fig. 11). As can be seen, the most cost-effective retrofit strategy for multi-span simply supported concrete girder bridge considering the seismic hazard of Charleston is seat extenders, which is followed by elastomeric isolation bearings. Note that this finding is consistent with the previous research [29]. Thus, the proposed methodology for identifying the most cost-effective measure of bridges is further validated.

In practice, however, there are some difficulties that may impede the application of the optimal seismic retrofit strategy in the design and construction process. To address this problem, the preferred retrofit strategy can be selected in order of RBCBRs. For the seat extenders, there are several forces that must be considered while the steel, which is employed to join seat extender to the face of cap beam or abutment, is designed. The complexity in the design of seat extenders may make this retrofit undesirable, and the elastomeric isolation bearings, steel jackets and restrainer cables are preferable. Although the elastomeric isolation bearings result in large RBCBRs when 0.1 g ≤ PGA ≤ 0.7 g, this retrofit strategy may not be desirable. For instance, if the normal operation of the bridge is required during retrofits, the elastomeric isolation bearings should not be considered due to their demand for temporary closure of the bridge. Then the steel jackets and restrainer cables are favorable. If the normal operation is also required for bridges crossing the river during retrofits, the steel jackets should not be considered due to corrosion and scour. Thus, the restrainer cables will be the preferable retrofit strategy when considering large earthquakes (0.8 g ≤ PGA ≤ 1.0 g) for this case. Considering the availability of local resources, construction technology, physical obstacle type that the bridge is built to span, and the other factors such as socioeconomic influences, the most cost-effective retrofit strategy is identified finally.

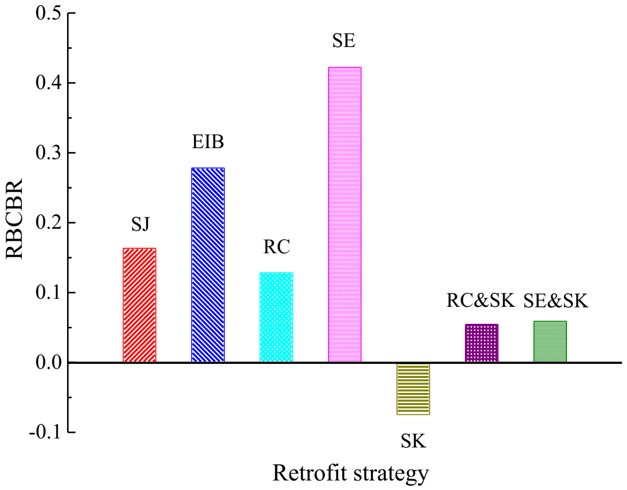


Fig. 11 Optimal retrofit strategy for multi-span simply supported concrete girder bridge in Charleston

In summary, RBCBA is a significant methodology for identifying the most cost-effective retrofit strategy for bridges. The optimal retrofit strategy varies with the bridge site due to the consideration of different regional seismic hazards. For the case study bridge located in Charleston, the most cost-effective retrofit strategy is seat extenders, which is followed by elastomeric isolation bearings. The availability of local resources, construction technology and damage conditions of bridges should also be considered in the application of a specific retrofit measure. If the optimal retrofit strategy is infeasible for a specific bridge, the preferred strategy can be selected in order of RBCBRs. The proposed methodology can also be used to identify the most cost-effective retrofit measure for building portfolios, highway transportation networks or communities. Besides, the methodology can be further developed to accommodate the other natural extreme events such as floods, hurricanes and be embedded in a comprehensive life-cycle management framework.

3.3 Sensitivity Study and Uncertainty Analysis

As previously noted, uncertainties in the estimation of RBCBRs arise from uncertainties in the parameters such as recovery time, control time and intensity measures. To identify major uncertain input parameters to which the RBCBRs are most sensitive, sensitivity study can be performed. For this, the scenario earthquake with PGA of 0.4651 g (5% exceedance probability in 50 years, Charleston) is considered. Since different major uncertain parameters can be identified when different bridges are considered, it is necessary to perform sensitivity analyses for all the bridges considered in the present study. Note that the analytical results from the sensitivity study are suitable for the bridges considered in the present study under some specific assumptions discussed above.

3.3.1 Uncertain Parameters

To perform sensitivity analysis, uncertain parameters should be established. The uncertain parameters considered in the present study are retrofit cost, control time and recovery time. It is assumed that these parameters are statistically independent, and the remaining parameters are kept at their respective mean values when one parameter varies. As previously noted, the proposed functionality assessment model is used to assess RBCBRs for retrofit strategies of bridges.

To determine the probability distribution of recovery times of bridges, the means and standard deviations of recovery times for each damage state shown in Table 2 are used. Since the retrofit costs are assessed based on a review of retrofit practices and associated cost estimation, it is assumed that retrofit costs follow a normal distribution with a coefficient of variation of 0.5. The control time, which is usually determined by bridge owners or stakeholders, can also be assumed to follow the normal distribution. To estimate the influence of control time on RBCBRs, it is assumed that the mean and standard deviation of control time are 22 days and 10 days, respectively. The detailed values for all uncertain parameters described above are listed in Table 8.

3.3.2 Sensitivity Analysis

To study the sensitivity of RBCBRs to the input uncertain parameters, tornado diagrams are used. This method helps to rank the contribution of each parameter to the uncertainties in RBCBRs. Again, one input parameter varies independently while all remaining parameters are kept at their respective mean values. Based on values of input parameters ranging from their low bounds, means—standard deviations, to upper bounds, means + standard deviations, the RBCBRs are estimated. The results are shown in Fig. 12, and the central solid lines show the most expected values of RBCBRs, which can be obtained when all input parameters are set to their respective mean values.

As shown in the figure, the recovery times and control times are the predominant parameters, which have a major influence on the RBCBRs. More specifically, the recovery time of as-built bridge and control time are the first two important sources of uncertainties in the RBCBRs for steel jackets and seat extenders, while RBCBRs are more sensitive to recovery times of as-built and retrofitted bridges for the remaining retrofit measures. This reveals that the methods for accurate estimation of recovery times and control time are sorely needed in order to improve the assessment of RBCBRs.

3.3.3 Uncertainties in Resilience-Based Cost–Benefit Analysis

After the identification of predominant sources of uncertainties, the Latin Hypercube random sampling technique [52], which has high efficiency compared with the Monte Carlo simulation, is used to generate random combinations of these major uncertain parameters. For steel jackets and seat

Table 8 Means and standard deviations of uncertain parameters

Parameters	Mean	SD	Parameters	Mean	SD
Recovery time $T_{\mathrm{RE},1}$-AB (days)	20	10	Control time T_{LC} (days)	22	10
Recovery time $T_{\mathrm{RE},2}$-SJ (days)	12	6	Retrofit cost C_2-SJ ($)	60,815	30,408
Recovery time $T_{\mathrm{RE},3}$-EIB (days)	15	8	Retrofit cost C_3-EIB ($)	24,142	12,071
Recovery time $T_{\mathrm{RE},4}$-RC (days)	17	9	Retrofit cost C_4-RC ($)	19,062	9531
Recovery time $T_{\mathrm{RE},5}$-SE (days)	14	7	Retrofit cost C_5-SE ($)	15,192	7596
Recovery time $T_{\mathrm{RE},6}$-SK (days)	25	13	Retrofit cost C_6-SK ($)	39,286	19,643
Recovery time $T_{\mathrm{RE},7}$-RC&SK (days)	17	9	Retrofit cost C_7-RC&SK ($)	58,348	29,174
Recovery time $T_{\mathrm{RE},8}$-SE&SK (days)	17	9	Retrofit cost C_8-SE&SK ($)	54,477	27,239

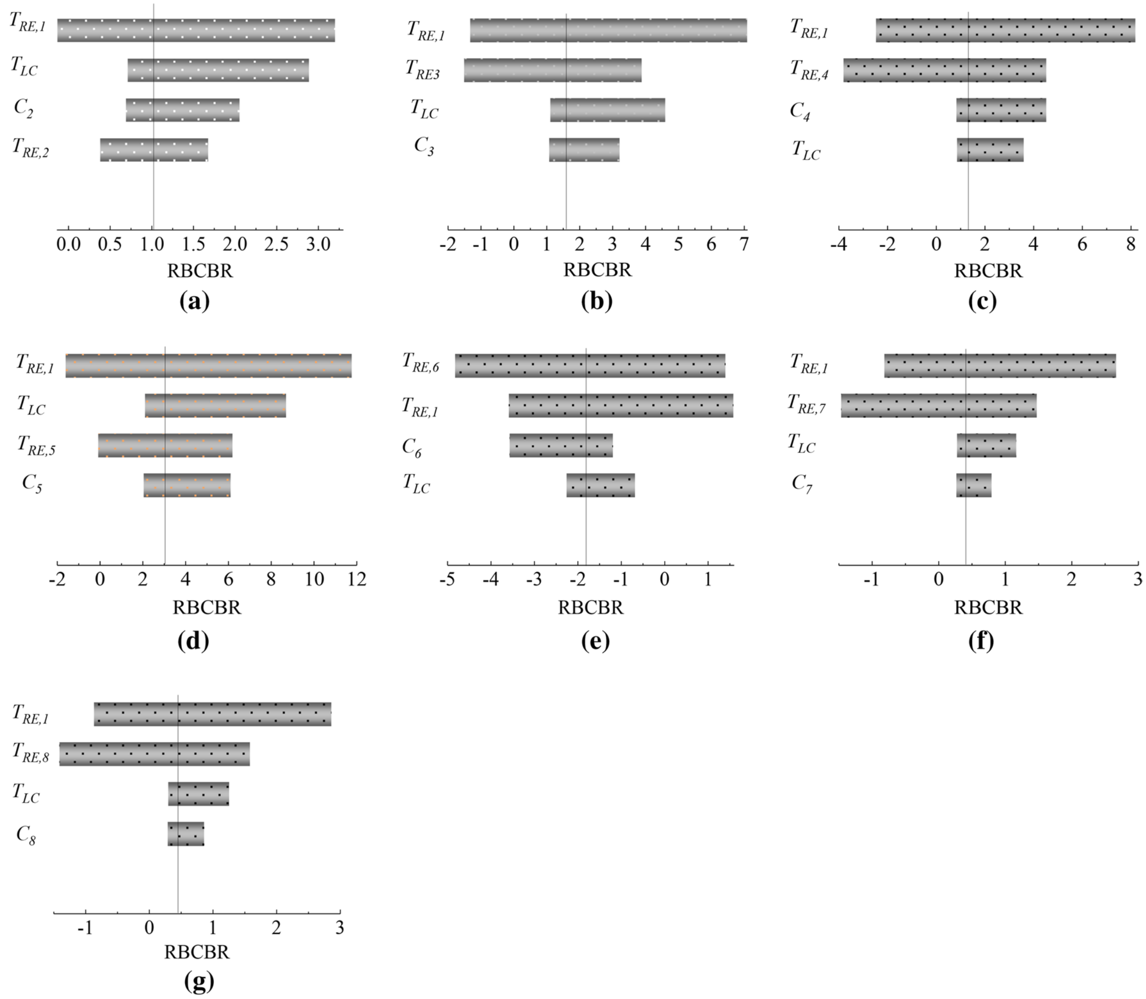


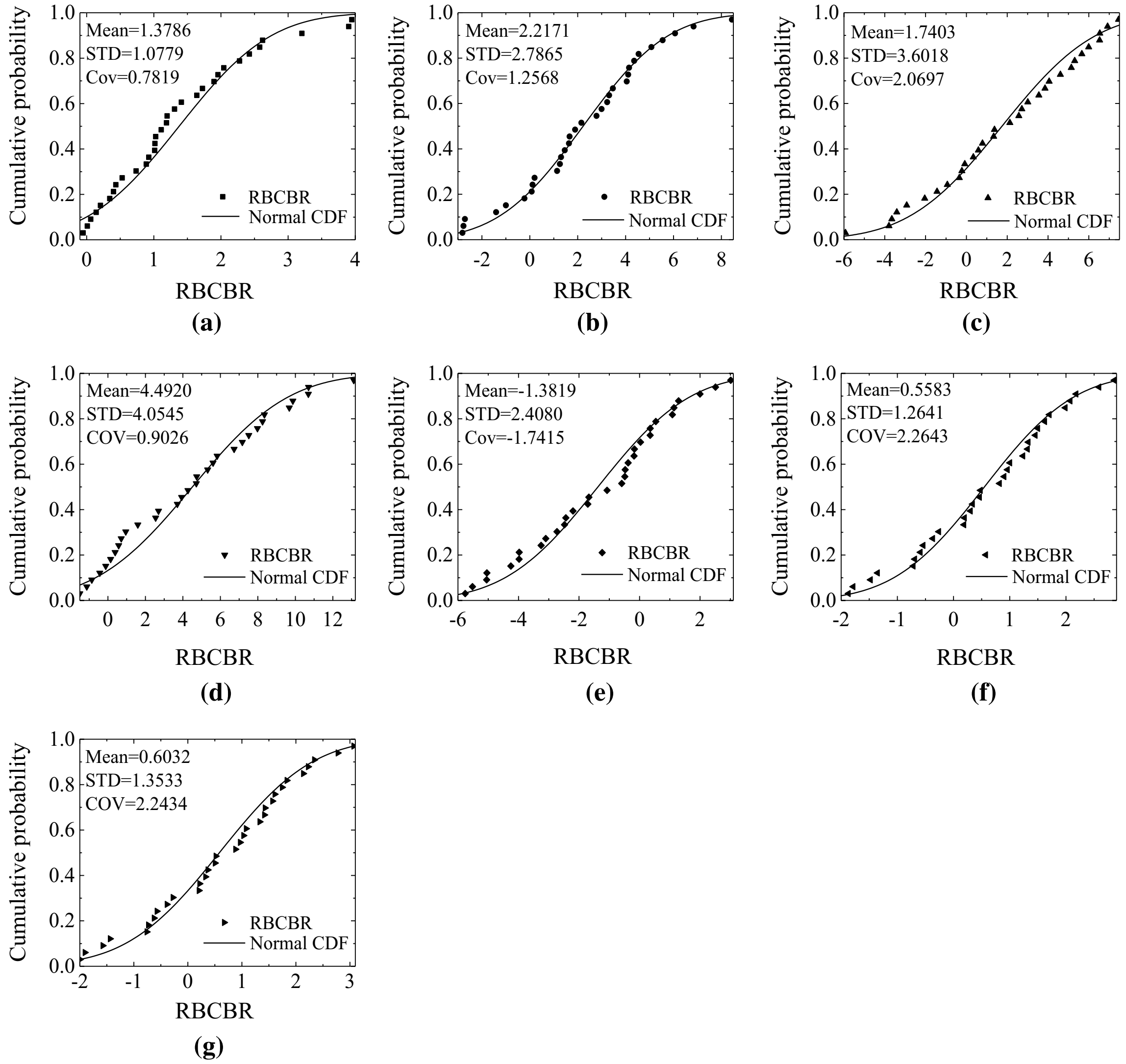
Fig. 12 Tornado diagrams for **a** SJ, **b** EIB, **c** RC, **d** SE, **e** SK, **f** RC&SK, and **g** SE&SK

extenders, normal distributions of the recovery time of as-built bridge and control time are used for random sampling, while recovery times of as-built and retrofitted bridges are considered for the remaining cases. According to the random sampling method used in the present study, 32 random combinations for each retrofit case are obtained. The RBCBRs are estimated for all combinations, and the mean, standard deviation and coefficient of variation values for each retrofit measure are also assessed (Fig. 13). To explain the statistical nature of RBCBRs, it is necessary to assume a potential distribution. The normal distribution stands out from all possible distributions based on goodness-of-fit tests. More specifically, the cumulative distribution function (CDF) of normal distribution and 32 values of RBCBRs are compared in Fig. 13, which shows high goodness-of-fit.

It should be noted that the distribution of RBCBRs may change if other distributions of recovery times and control time are considered. Thus, it is necessary to choose an appropriate distribution for each input parameter in order to improve the accuracy of the assessment of RBCBRs. To further consider uncertainty in the RBCBRs, the 90% confidence intervals (between 5% and 95% confidence levels) of RBCBRs are estimated (Table 9). The results also show the high cost-effectiveness of seat extenders, elastomeric isolation bearings and restrainer cables to enhance seismic resilience of multi-span simply supported concrete girder bride considering the retrofit costs and regional seismic hazards.

4 Summary and Conclusions

The probabilistic resilience-based cost–benefit analysis model presented in this paper can be used to identify the most cost-effective retrofit strategy for bridges in seismic zones. The methodology integrates the functionality analysis model, seismic loss models and retrofit costs. Unlike



(a) (b) (c) (d) (e) (f) (g)

Fig. 13 Uncertainties in resilience-based cost–benefit ratios for **a** SJ, **b** EIB, **c** RC, **d** SE, **e** SK, **f** RC&SK, and **g** SE&SK

Table 9 Resilience-based cost–benefit ratios with 90% confidence intervals

Retrofit strategy	Resilience-based cost–benefit ratio		
	95% CI	50% CI	5% CI
SJ	0.990	1.378	1.767
EIB	1.212	2.217	3.222
RC	0.442	1.740	3.039
SE	3.030	4.492	5.954
SK	− 2.250	− 1.382	− 0.514
RC&SK	0.103	0.558	1.014
SE&SK	0.115	0.603	1.091

cost–benefit analysis, which only considers economic dimension as benefit, the increase in resilience is used as the total benefit of seismic retrofit in the resilience-based cost–benefit analysis. The enhancement of resilience can consider the influence of important benefits such as reduced failure probabilities of structures, alleviation of negative consequences because of failures (e.g., socioeconomic consequences) and rapid recovery after earthquakes.

The multi-span simply supported concrete girder bridge located in Charleston, South Carolina is considered as a case study to illustrate the application of the resilience-based cost–benefit analysis model. Seven different retrofit strategies are used for the seismic upgrade of the bridge. Seismic resilience of as-built and retrofitted bridges are estimated based on the proposed functionality assessment model, which is validated according to the field data of post-earthquake recovery of the medium bridge in China. Then the resilience-based cost–benefit analysis of retrofit measure is performed by combining the increment of resilience and the associated retrofit cost. The results reveal that the optimal retrofit varies with ground motion intensities, and seat extenders are the most cost-effective retrofit strategy followed by elastomeric isolation bearings when considering the seismic hazard of Charleston. The methodology also suggests a possible selection sequence for the optimal seismic retrofit measures.

The sensitivity study are performed to identify the uncertain parameters to which the resilience-based cost–benefit ratios are more sensitive. The results indicate that the recovery times of as-built and retrofitted bridges and the control time contribute significantly to the uncertainties in the RBCBRs, while uncertainties from retrofit costs can be neglected. The RBCBRs estimated from the random sampling of major uncertain input parameters show that the statistical nature of RBCBRs can be described by a normal distribution. The 90% confidence intervals of RBCBRs also show the high cost-effectiveness of seat extenders and elastomeric isolation bearings to improve the seismic performance of bridges.

Note that the most cost-effective retrofit measure, major uncertain input parameters, and the uncertainties in RBCBRs identified in the paper are specific to the case study bridge. More general conclusions can be obtained through analysis of a large population of bridges during all possible ground motion intensities. According to the locations, site conditions, seismic hazard levels, local economic conditions, and acceptable downtime after seismic events, the most cost-effective retrofit strategy of bridges can be identified by resilience-based cost–benefit analysis. Future work shall include the application of life-cycle resilience-based cost–benefit analysis, which can also be used to identify the most cost-effective retrofit measure for bridges. It should be noted that the proposed methodology can be extended to identify the most cost-effective seismic retrofit strategy for building portfolios, highway transportation networks or communities.

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