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Optimizing Retrofit Strategies for Irregular Structures Under Seismic Loads: A Performance-Based Risk Approach

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Abstract. Irregular structures often exhibit inadequate behavior under seismic loads, resulting in higher levels of damage when compared to regular structures. This represents a challenge that underscores the necessity of exploring strategies to enhance their performance and reduce associated risks. One promising solution corresponds to developing effective retrofit alternatives to optimize structural behavior and minimize expected losses. This work aims to assess the seismic performance of irregular structures using braces as a retrofit strategy. The primary goal is to determine the optimal brace cross-sectional area that balances construction and repair costs, achieving a cost-effective solution. The methodology integrates Performance-Based Earthquake Engineering (PBEE) principles with a novel Performance-Based Risk Optimization (PBRO) framework. A surrogate modeling approach is employed to model Engineering Demand Parameters (EDPs), leveraging a Kriging metamodel. This metamodel estimates the median and standard deviation of the EDPs, assuming a lognormal distribution, to capture the variability and uncertainty in seismic responses. The proposed approach is validated through a case study of an irregular steel building. The study evaluates the structure's performance both with and without the retrofit braces. Then, a multi-objective optimization process is conducted to identify the cross-sectional area of the braces that minimizes the combined costs of construction and expected repairs. The optimization framework incorporates the FEMA P-58 [1] methodology, ensuring a comprehensive evaluation of seismic performance and associated risks. The findings contribute to advancing the understanding of irregular structures subjected to seismic actions. The results provide a practical guide for identifying cost-effective retrofit solutions, offering valuable insights for practitioners and researchers in the field of earthquake engineering.

Keywords: Performance-Based Risk Optimization, Irregular buildings, Metamodels

1 Introduction

Irregular buildings are among the primary contributors to structural damage during earthquakes, often leading to collapse and casualties. Despite their significance, research on this topic remains limited, resulting in a lack of well-established design guidelines. Structural irregularities are typically classified into mass and stiffness asymmetries, as well as plan and vertical irregularities [2]. The primary consequences of such irregularities include altered displacement patterns and increased ductility demands in the affected regions [3], both of which have been widely observed in past earthquake events. Furthermore, Saeedi et al. (2024) [4] emphasize the potential for progressive collapse in irregular structures subjected to seismic loading.

To assess the seismic performance of irregular structures in a comprehensive and reliable manner, the Performance-Based Earthquake Engineering (PBEE) framework is a suitable approach. By aiming to predict and evaluate structural performance with sufficient confidence to satisfy societal safety and functionality objectives [5, 6], PBEE provides a rational basis for addressing the complex demands imposed by irregular configurations during seismic events.

In the context of irregular structures, where complex dynamic behaviors and increased vulnerability demand more refined engineering strategies, optimization becomes essential to balance performance and efficiency. Within the PBEE framework, optimization can be naturally incorporated by adopting total expected losses as the decision-making metric. However, a major challenge lies in the need to evaluate probabilistic constraints within the optimization loop, which is computationally intensive [7–9].

Given the challenges associated with the seismic assessment of irregular buildings, this work investigates the use of Buckling Restrained Braces (BRBs) as a strategy to improve their structural response under seismic loading. BRBs are concentric metallic elements specifically designed to resist lateral loads without experiencing local buckling [10]. When integrated into the structural system, these braces contribute both to lateral stiffness and energy dissipation by stabilizing the moment-resisting mechanism and concentrating damage within the brace core, thereby reducing the structure's inelastic demands.

To evaluate the effectiveness of BRBs in enhancing the seismic performance of irregular buildings, this study adopts the Performance-Based Risk Optimization (PBRO) framework proposed in Rodrigues et al. (2025) [11]. The objective is to determine the optimal BRB configuration by balancing initial construction costs and expected repair costs in a five-story irregular special moment-resisting frame. The framework employs Gaussian Process surrogate models to replace high-fidelity finite element analyses when estimating the jointly lognormal parameters of Engineering Demand Parameters (EDPs), as defined in FEMA P-58.

2 Performance-Based Risk Optimization (PBRO)

Performance-based seismic design consists of designing new structures or retrofitting existing ones to satisfy predefined performance objectives. In this context, the primary goal is to estimate the mean annual frequency with which critical performance metrics—referred to as decision variables—exceed specified thresholds. These decision variables may include, for example, casualties, economic losses, or repair times. Modern formulations adopt the framework proposed by the Pacific Earthquake Engineering Research Center (PEER) [12], which relies on the total probability theorem to quantify seismic risk. The mean annual frequency of exceeding a given threshold for a decision variable, dv, is expressed as [13]:

$$\lambda\left(DV > dv\right) = \int_{im}\int_{dm}\int_{edp} G\left(dv|dm\right) dG\left(dm|edp\right) dG\left(edp|im\right) \left|d\lambda\left(im\right)\right| \tag{1}$$

where im is the seismic intensity measure; edp are the engineering demand parameters; dm is the damage measure; and $\lambda(im)$ is the seismic hazard curve. The nested conditional distributions reflect uncertainty propagation from seismic hazard to structural response, damage, and ultimately decision variables.

Within the Performance-Based Earthquake Engineering (PBEE) framework, optimization techniques can be naturally incorporated to identify structural configurations that achieve an optimal balance between construction cost and seismic risk. In this context, the present study adopts a Performance-Based Risk Optimization (PBRO) formulation, which aims to minimize the combined cost of construction and the expected annual repair losses. The problem is formulated as the following multi-objective optimization problem:

$$\begin{aligned} &\text{Find} \quad \mathbf{x} = \{x_1, \dots x_N\}^T \\ &\text{to minimize} \quad W(\mathbf{x}) = \{C_{\text{cons}}(\mathbf{x}), C_{\text{exReCo}}(\mathbf{x})\}^T \\ &\text{subject to} \quad \mathbf{x} \in \mathcal{X} \end{aligned} \tag{2}$$

where $\mathbf{x}$ is a N-dimensional vector of design variable belonging to design space $\mathcal{X} \in \mathbb{R}^N$; $C_{\text{cons}}(\mathbf{x})$ is the construction cost; and $C_{\text{exReCo}}(\mathbf{x})$ represents the expected annual repair, demolition, and collapse costs, which in general depends on the mean annual rate $\lambda(DV > dv)$.

3 Proposed Approach

This study aims to evaluate the improvement in structural seismic performance achieved by incorporating BRBs into irregular buildings. Initially, a set of nonlinear static analyses is performed to quantify the improvement in structural capacity that the use of BRBs can bring to the structure. Following this assessment, the cross-sectional areas of the BRBs are optimized considering the PBRO methodology developed in [11]. The optimization framework relies on a noisy metamodel framework that incorporates statistical variability trained on a reduced set of nonlinear time history analysis (NLTHA) to efficiently identify optimal retrofit solutions.

3.1 Nonlinear static Pushover Analysis

Pushover analysis is a nonlinear static procedure carried out under constant gravitational loads and monotonically increasing lateral loads. Its primary objectives are to assess the structural performance of buildings through capacity curves—i.e., base shear versus Interstory Drifts—and to estimate the expected plastic mechanism and the distribution of damage throughout the structure. Pushover analysis is addressed in several design standards, each incorporating different considerations regarding its procedures and the prescribed vertical distribution of lateral loads [14, 15].

3.2 PBRO Approach

To solve the PBRO problem defined in this study for optimizing the BRB areas in the irregular structure, the methodology proposed by Rodrigues et al. (2025) [11] is adopted. This approach relies on a noisy Kriging metamodel to estimate the population values of the distribution parameters that characterize the joint distribution of the vector of Engineering Demand Parameters (EDPs), explicitly accounting for the statistical uncertainty associated with the estimated distribution parameters.

According to the formulation of $C_{exReCo}(\mathbf{x})$, a nonlinear finite element model must be evaluated through NLTHA in order to infer the statistical distributions of the EDPs, which depend on each design point (i.e., candidate vector $\mathbf{x}$). In other words, the expected repair cost is a function of the following parameters obtained from the structural model:

- First mode period of the structure $\bar{T}(\mathbf{x})$, obtained through a modal analysis.
- Parameters of the EDPs, represented by a joint lognormal distribution characterized by the mean $\mu_{EDP_i}(\mathbf{x})$, standard deviations $\sigma_{EDP_i}(\mathbf{x})$, and correlation terms $\rho_{EDP_{ij}}(\mathbf{x})$s.

The expected repair cost can be written in terms of a general implicit nonlinear function, g_{NL}, as:

$$C_{\text{exReCo}}(\mathbf{x}) = g_{\text{NL}}\left(\bar{T}(\mathbf{x}), \mu_{EDP_i}(\mathbf{x}), \sigma_{EDP_i}(\mathbf{x}), \rho_{EDP_{ij}}(\mathbf{x})\right) \tag{3}$$

where $i, j = 1, 2, \ldots, N_p$, with N_p is the number of EDPs, i.e., components of $\mathbf{EDP}$.

The methodology detailed in [11] replaces the Finite Element model necessary to obtain the demand parameters with a Kriging metamodel [16]. An interpolation is considered for the first mode period of the structure, indicated as $\tilde{\mathcal{M}}_{\bar{T}}(\mathbf{x})$, and Kriging regressions (noisy Kriging) for the statistics of the key response parameters of the structure, indicated as $\hat{Y}_{\mu_{EDP_i}(\mathbf{x})}$ and $\hat{Y}_{\sigma_{EDP_i}(\mathbf{x})}$. It is assumed that the correlation matrix $\rho_{EDP_{ij}}$ is weakly dependent on $\mathbf{x}$.

After training these intermediate metamodels to estimate the distribution parameters of the EDPs, a final Kriging model, $\tilde{C}_{\text{exReCo}}(\mathbf{x})$, is constructed to approximate the expected repair cost directly over the design space. This additional surrogate significantly reduces the computational cost of the optimization process by encapsulating the influence of the underlying models. Within this formulation, Eq. (3) can be rewritten as:

$$\tilde{C}_{\text{exReCo}}(\mathbf{x}) = \tilde{\mathcal{M}}_{\tilde{g}_{\text{NL}}}\left(\tilde{\mathcal{M}}_{\bar{T}}(\mathbf{x}), \hat{Y}_{\mu_{EDP_i}}(\mathbf{x}), \hat{Y}_{\sigma_{EDP_i}}(\mathbf{x}), \bar{\rho}_{EDP_{ij}}\right) \tag{4}$$

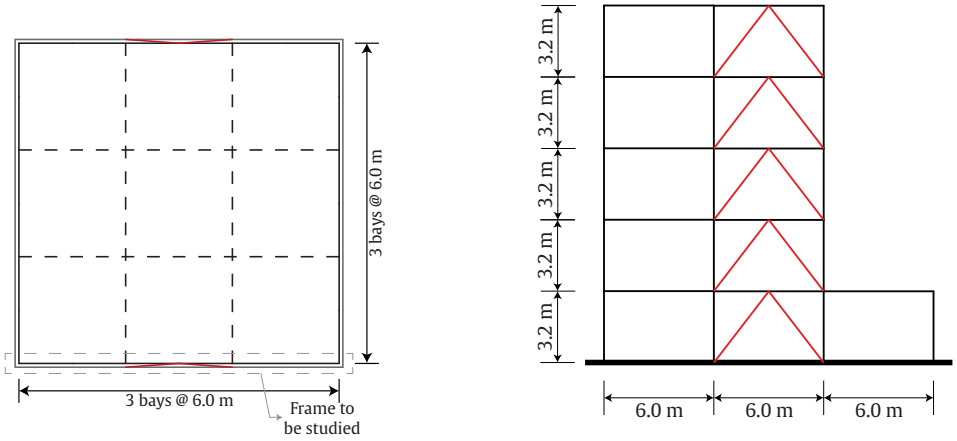
Further details on how statistical uncertainty is incorporated into the proposed noisy Kriging framework can be found in [11].

4 Case Study

The irregular building evaluated in this case study was presented by Saeedi et al. (2024) [4] and corresponds to a five-story special moment-resisting frame with an irregularity of 26.67%. The building design follows AISC 360 [17] and AISC 341 [18]. BRBs are incorporated into the building's design. Beams and columns are constructed from Steel St 37, which has yield and ultimate stresses of 240 MPa and 370 MPa, respectively. The steel considered in the core of the BRB section corresponds to the ASTM A36 material. Figure 1 illustrates the structure considered in this case study, with the typical plan view shown in Figure 1a and the elevation of the perimeter frame depicted in Figure 1b. The BRBs are represented in red in Figure 1b.

A two-dimensional representation of the archetype steel building is developed using OpenSees software [19], leveraging its library to define beam and column elements. The geometric properties of these structural components are provided in Table 1.

The model of beams and columns considers the displacement-based beam-column elements with distributed plasticity. Each element is discretized with five integration points, incorporating six fibers along the depth and thickness of the web, as well as the breadth of the flange. The cyclic behavior of steel in beams and columns is



(a) (b)

Figure 1. Case study structure: (a) typical plan view of the building; (b) representation of the irregular building.

Table 1. Member Design Sections

Story	Beam Size	Column Size
1	W18X71	HSS14X14X5/8
2	W18X86	HSS14X14X5/8
3	W18X86	HSS12X12X5/8
4	W16X50	HSS12X12X5/8
5	W16X50	HSS10X10X5/8

modeled using the *Steel02* material from the OpenSees library, as formulated by Guiffré-Menegetto-Pinto [20]. A modulus of elasticity of 200 GPa and a yield strength of 240 MPa are assumed, with an isotropic strain hardening ratio of 1%. To account for inherent damping, the Rayleigh damping model is applied, considering a damping ratio of 2% for the first and third vibration modes of the structure. Additionally, P-Delta effects are incorporated into the column modeling.

Buckling Restrained Braces (BRBs) are incorporated in the model using a corotational truss element available in OpenSees. The BRBs are modeled with the *SteelBRB* elastoplastic material, originally proposed by Zona and Dall'Asta [21] and later implemented in OpenSees by Gu et al. [22]. The material properties considered in the Finite Element model includes the Young's modulus ($E = 200GPa$), the core yield stress ($F_y = 370MPa$), and the maximum yield forces under fully saturated isotropic hardening conditions in both tension ($F^+_{y,max} = 492.10MPa$) and compression ($F^-_{y,max} = 580.68MPa$).

4.1 Pushover Results

The first evaluation of the irregular building consists of a static pushover analysis, aimed at comparing the maximum lateral capacity of the structure with and without BRBs, as well as estimating the distribution of damage throughout the building. A rectangular load pattern was adopted, and the capacity curve was obtained by relating the displacement at the top of the structure to the total base shear recorded during the analysis. For the system with BRBs, a cross-sectional area of $A_{BRB} = 32.25\,cm^2$ was used for all stories of the building. The results of the Static Pushover analysis and the Capacity Curve for the buildings without and with the BRBs are represented in Figure 2.

It is important to note that the model without BRBs did not converge for displacements beyond the point indicated in Figure 2. Additionally, the improvement in structural capacity provided by the inclusion of BRBs is clearly observable. The fundamental period of the structure without BRBs is $T = 0.832\,s$, whereas the period of the structure with BRBs is reduced to $T = 0.374\,s$. This reduction reflects an increase in system stiffness and strength, which is also illustrated in Figure 2.

In order to evaluate the distribution of damage throughout the structure, the deformed shape and the stress

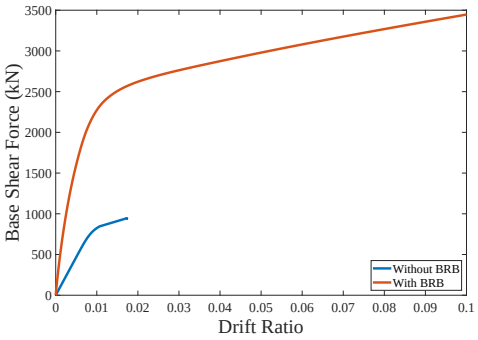
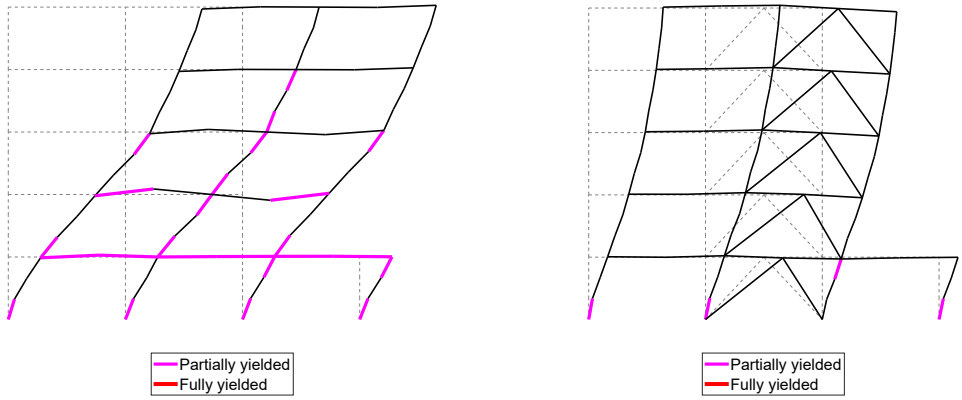


Figure 2. Capacity Curve for the irregular building without and with the BRBs.

state of all elements were examined at a specific instant of the static analysis. The corresponding plots are presented in Figure 3, with the respective base shear value indicated for each case. Figure 3a shows the yielded elements for the structure without BRBs, while Figure 3b shows the yielded elements for the structure with BRBs.



(a) Base Shear Force of $946.4\,kN$ (b) Base Shear Force of $1866.7\,kN$

Figure 3. Deformed shape with partially and completely yielded components for a specific step of the Pushover analysis.

It can be observed that the system with BRBs exhibits nearly twice the lateral capacity of the structure without BRBs, with significantly fewer elements reaching yielding. Moreover, in the structure with BRBs, yielding is primarily concentrated in the first story, indicating a more controlled and localized energy dissipation mechanism. In contrast, the structure without BRBs shows widespread yielding throughout its height, suggesting a less efficient and more dispersed plastic mechanism. This result validates the effectiveness of BRBs in enhancing the structural capacity under static loading. The following section presents an optimization of the BRB cross-sectional areas, adopting a Performance-Based Risk Optimization approach under seismic loading.

4.2 Optimization Problem

The main goal of this case study is to optimize the areas of the BRBs in all stories of the building. In the proposed optimization problem, the design variables are the BRB areas for the first story ($A_{BRB,1}$), second story ($A_{BRB,2}$), third story ($A_{BRB,3}$), fourth story ($A_{BRB,4}$) and fifth story ($A_{BRB,5}$), and the optimization problem is represented by:

$$\begin{aligned} &\text{Find } \mathbf{x^*} = \{A_{BRB,1}, A_{BRB,2}, A_{BRB,3}, A_{BRB,4}, A_{BRB,5}\}^T \\ &\text{to minimize } W(\mathbf{x}) = \left[C_{cons}(\mathbf{x}) + \tilde{C}_{exReCo}(\mathbf{x})\right] \\ &9.7 \leq \{A_{BRB,i}\}_{i=1}^{5} \leq 64.5\,cm^2 \end{aligned} \tag{5}$$

where $C_{cons}(\mathbf{x})$ represents the initial construction cost of the structural steel frame (including beams, columns, and BRBs), and $\tilde{C}_{exReCo}(\mathbf{x})$ is the expected annual repair cost, calculated based on the FEMA P-58 methodology [1], using the surrogate model approximations.

It is important to mention that a multi-objective optimization for this case study has already been developed in [23].The construction cost of the steel frame, indicated in Equation 5 as $C_{cons}(\mathbf{x})$, is estimated as follows:

$$C_{cons}(\mathbf{X}) = C_{steel}(W_{beams} + W_{columns}) + C_{BRB}W_{BRB} \tag{6}$$

where C_{steel} corresponds to the cost of the steel, C_{BRB} represents the cost of the BRBs, and W_{beams}, $W_{columns}$, and W_{BRB} indicate the weight of the beams, columns, and BRBs, respectively.

Costs for steel and BRBs adopted in this work are: $C_{steel} = \$4.72/kg$ [24] and $C_{BRB} = \$8.99/kg$ [25]. For beams and columns, the nominal weight is obtained from the AISC database - v16.0 [17]. For the BRBs, weight is calculated as: $W_{BRB} = A_{BRB} \times L_{BRB} \times \rho$, where L_{BRB} is the length of the element, and ρ is the density of the material, which for ASTM A36 steel is $\rho = 7850\,kg/m^3$.

Based on the FEMA P-58 methodology, calculating the expected annual repair and reconstruction cost, $\tilde{C}_{exReCo}(\mathbf{x})$, requires defining the building performance model. In this case study, the irregular building is assumed to function as an office space, with a floor area of $324\,m^2$ in the first floor and $216\,m^2$ in the other floors. The RSMeans Project Cost database is used to estimate the building's Replacement Cost, assuming its location is in urban California. For a commercial office in this region, the construction cost is estimated at $\$\,2093.75/m^2$. To account for costs independent of their proximity to the total Replacement Cost, the total Loss Threshold is set at 100%. Environmental impacts are not considered in this study but could be incorporated in future assessments.

For building repair activities, the workforce is set at one worker per 1,000 square feet of floor area, following FEMA P-58 recommendations [1]. This corresponds to approximately one worker per $100\,m^2$. The building's population model is classified under "Commercial Office" occupancy, with an expected peak population of four persons per 1,000 square feet, or roughly four persons per $100\,m^2$. Additionally, the model accounts for variations in occupancy throughout the day on both weekdays and weekends.

The fragility function database, developed using the PACT tool [26], is employed in the building performance models, reflecting the specified building contents. The corresponding demand parameters for each fragility function are the Story Drift Ratio (SDR) and Peak Floor Acceleration (PFA). Component categories are classified as follows: B for shell components, C for interior components, D for service components, and E for equipment and furnishing components. The quantities of each component are determined using the Normative Quantity Estimation Tool available in the FEMA P-58 support materials [1].

The hazard is defined based on the 5% damped Target Hazard Spectrum for a 2% probability of exceedance in 50 years (2/50). The building is assumed to be located in Los Angeles on soil type C. Seismic hazard curves are obtained from the U.S. Geological Survey (USGS) tool [27] and used to generate the hazard spectrum following the ASCE standard [28].

The stochastic ground motion model employed in this work corresponds to a point-source model that takes into account both the physics of fault rupture and wave propagation. As implemented in [29, 30], these models are based on a parametric description of the ground motion's radiation spectrum, which is dependent on the earthquake magnitude M and the epicentral distance r, and is expressed as a function of frequency. The bounded Gutenberg-Richter recurrence relationship is used to model the moment magnitude M as a truncated exponential distribution [30], with minimum and maximum values of magnitude considered are $M_{min} = 6$ and $M_{max} = 8$. The epicentral distance is considered as a lognormal distribution with a median of $2.5\,km$ and a coefficient of variation of 0.4.

To address the problem described in Equation 5, 50 sample points are selected as the Design of Experiments (DoE) considering Latin Hypercube Sampling (LHS). The DoE is used to calibrate the Kriging metamodel, which serves as a surrogate for the high-fidelity nonlinear Finite Element model in the optimization process. The Engineering Demand Parameters considered in this problem are: Interstory Drifts of stories 1 ($Drift_1$), 2 ($Drift_2$), 3 ($Drift_3$), 4 ($Drift_4$), 5 ($Drift_5$); Peak Floor Acceleration of floors 1 (PFA_1), 2 (PFA_2), 3 (PFA_3), 4 (PFA_4), 5 (PFA_5), 6 (PFA_6); Residual Drift (RDR).

A parent set of 500 hazard-consistent earthquake records is generated using the Stochastic Ground Motion model. From this set, 10 distinct ground motion groups are created, each containing 24 signals ($N_e = 24$), reflecting the number of earthquakes typically used in practical design applications. To capture the statistical variability in hazard representation, the selection of signals for each group is entirely random, ensuring no repetition across different sets.

All surrogate models developed in this example share the following configurations: ellipsoidal correlation type, anisotropic correlation, and the Maximum Likelihood Estimation (MLE) method. The key distinctions among these surrogate models stem from variations in the Kriging trend and the correlation families employed. The surrogates for the EDPs consider a linear trend and an Exponential correlation family, except for the Residual Drift (RDR). To enhance the accuracy of the surrogate model, a quadratic trend was adopted for the ***RDR*** surfaces [31]. Likewise, the interpolation of the expected annual repair cost, $\tilde{C}_{exReCo}$, yielded lower errors when applying

a quadratic trend in combination with a Gaussian correlation family. It is important to mention that this case study does not consider surrogates for the collapse fragility function, as the collapse assessment was not implemented in this study.

The optimization problem in this case study is addressed using the Genetic Algorithm (GA) [32]. A population size of 50 points is considered for the solution process. For each point in the population, the Kriging surface for expected repair cost is evaluated. The results are presented in Table 2.

Table 2. Results for the Risk Optimization (RO) problem.

$A_{BRB,1}$ (cm^2)	$A_{BRB,2}$ (cm^2)	$A_{BRB,3}$ (cm^2)	$A_{BRB,4}$ (cm^2)	$A_{BRB,5}$ (cm^2)	$W(\mathbf{x})$ (\$) Surrogate	$\tilde{C}_{exReCo}(\mathbf{x})$ (\$) Surrogate
15.24	33.14	64.50	64.50	44.80	1.41×10^6	1.28×10^6

The results of the Risk Optimization problem indicate that the BRB areas should be increased in all stories above the first floor, particularly in the third and fourth stories. In these levels, the BRB area reaches the upper limit of the design domain to effectively reduce the expected repair cost while maintaining a balance with the initial construction cost. In contrast, in the first story, the BRB area can remain close to the minimum, suggesting that damage is significantly greater in the stories where the building exhibits structural irregularities.

These findings demonstrate that the proposed framework can assist in prioritizing floors when a building retrofit is required, guiding decision-making to enhance seismic performance efficiently.

5 Conclusions

This study presented an integrated framework for assessing and optimizing the seismic performance of irregular structures equipped with BRBs. The approach combined nonlinear structural analysis with a surrogate-based optimization method grounded in PBEE principles. Static and dynamic evaluations were performed to quantify the benefits of incorporating BRBs, followed by a PBRO procedure to identify efficient retrofit configurations.

The results confirmed that BRBs significantly enhance the structural response by increasing lateral strength and reducing damage concentration. Moreover, the PBRO methodology effectively prioritized the allocation of BRB capacity throughout the structure, identifying the floors that required larger brace areas. In comparison with results obtained for regular buildings, the optimized BRB areas in irregular configurations exhibited greater variation across floors and reached the upper bound of the design domain on the third and fourth floors [11]. This targeted distribution supports the development of more efficient and risk-informed retrofit strategies.

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