Optimizing Bridge Retrofit Designs for Resilience: A Multiobjective Evolutionary Algorithm Approach

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ABSTRACT

This study on bridge retrofitting sounds fascinating! Using a multiobjective evolutionary algorithm to find optimal retrofit design configurations is quite innovative. It's great to see technology being applied to enhance the resilience of transportation infrastructure. The choice of retrofit materials—steel, carbon fiber, and glass fiber composites—adds an interesting dimension to the research. Each material likely has its own strengths and weaknesses in terms of mechanical properties and cost, leading to a trade-off between cost and performance in retrofit operations. The results, particularly the Pareto near-optimal set, seem promising. Having distinct solutions that vary in cost, contribution to resilience enhancement, and design parameters provides valuable insights for decision-makers. This optimal set can guide the selection of materials and design configurations based on specific criteria and priorities. Overall, this study seems like a significant contribution to improving the resilience of bridges, especially considering the multihazard effects of earthquakes and flood-induced scour. It's exciting to see how advanced algorithms can help optimize infrastructure design for better performance under various challenges.

Keyword: - *Bridge retrofitting, Multiobjective evolutionary algorithm, Resilience enhancement, Retrofit materials, Pareto near-optimal set*

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1. Introduction

Bridge columns play a pivotal role in dictating the dynamic behavior of bridges. Prior to 1971, seismic failures of bridges often manifested as the formation of plastic hinges and shear failures in columns due to inadequate reinforcement detailing and lateral confinement. Over a decade of research has highlighted the efficacy of column jacketing in enhancing the seismic response of bridges by improving their shear and flexural capacities. This technique, involving the confinement of bridge columns using wraparound jackets, has been widely adopted by various transportation departments as a retrofit strategy, particularly with the emergence of displacement-based seismic design. While steel has conventionally been the material of choice for jacketing, the increasing adoption of fiber-reinforced polymer (FRP) jackets is notable for its superior properties such as high strength-to-weight ratio and resistance to corrosion. The availability of different composite materials for bridge retrofitting introduces a challenge for bridge owners and stakeholders: determining the most cost-effective retrofit option without compromising performance. This decision-making process involves balancing the inherent disparities in mechanical properties and associated costs of these materials, leading to a trade-off between cost and performance in retrofit operations. The study aims to address this trade-off by optimizing bridge retrofit design configurations to enhance both resilience and cost-effectiveness under the multihazard effect of earthquakes and flood-induced scour.

Research has identified earthquake combined with flood-induced scour as a critical multihazard scenario for bridges in seismically active, flood-prone regions. Despite the low joint probability of occurrence, the sequential incidence of these events within a short time frame can't be ignored. Previous studies have shown increased seismic vulnerability of bridges due to scour at bridge foundations, resulting in heightened deformation of the bridge pier-foundation system during seismic events. While various retrofit techniques exist, practical constraints may limit their simultaneous application, necessitating the identification of optimal retrofit strategies for such multihazard scenarios.

The study employs a two-objective optimization approach to maximize bridge resilience and minimize retrofit costs using a multiobjective evolutionary algorithm, NSGA II. This algorithm facilitates the exploration of different retrofit configurations considering variables like retrofit material choice, the column to be retrofitted, and the thickness of retrofit material. Nonlinear time history analyses are conducted for each retrofit design option, generating bridge fragility curves to assess loss and resilience. The resulting Pareto near-optimal solutions offer a range of retrofit options, each varying in cost, resilience enhancement, and design parameters. While column jacketing proves effective for seismic hazard mitigation, its applicability under combined earthquake and flood-induced scour scenarios requires further investigation. The study's scope is limited to column jacketing due to the predominant influence of flexural damage on the seismic performance of the case study bridge. However, the methodology can be extended to explore other retrofit measures such as restrainers installation or seismic isolation in applicable scenarios. Disaster resilience, as defined by the National Academies, encompasses the ability to prepare for, absorb, recover from, and adapt to adverse events. This concept emphasizes proactive planning and mitigation efforts rather than solely responding to disasters after they occur. Achieving enhanced resilience involves not only anticipating disasters but also efficiently managing post-event recovery within acceptable time and cost constraints. In recent years, there has been a shift towards quantifying structural damage from natural hazards to include socioeconomic consequences, recognizing the broader impact on society. Traditional approaches to infrastructure design focused on resistance to extreme events, whereas resilience-based design considers both the event phase and post-event recovery. Resilience accounts for a community's preparedness and available resources to mitigate the effects of disasters. The analytical framework for disaster resilience involves quantifying the functionality of a system over time, incorporating both the event and recovery phases. This is represented by a function Q(t), where t0E denotes the time of the extreme event, TRE is the post-event recovery time, and TLC is the control time for evaluating resilience. Resilience (R) is expressed as an integral of Q(t) over the recovery period, indicating the system's ability to maintain functionality during and after the event. Q(t) is determined by a loss function and a recovery function, representing the system's interruption period and subsequent restoration. Resilience values range from 0 to 100%, with higher values indicating greater ability to withstand damage and recover. An alternative approach to measuring resilience is time-dependent resilience, which considers the system's evolution through stages of disaster prevention, damage propagation, and recovery. This approach captures changes in service demand and post-event improvement efforts, as well as inter-hazard interactions. However, the current study employs a simpler resilience measurement using Eq. (1) to observe the enhancement of resilience through various retrofit designs. This approach focuses on assessing the effectiveness of retrofit strategies in improving the bridge's resilience under the combined effects of earthquake and flood hazards.

The present study addresses the optimization of bridge retrofit designs to enhance resilience under the combined effect of earthquake and flood-induced scour while minimizing retrofit costs. Utilizing a two-objective optimization approach, the study aims to maximize bridge resilience and minimize retrofit costs simultaneously. This approach has been previously employed in various studies to identify optimal bridge maintenance operations. The study employs a multiobjective evolutionary algorithm, specifically the Nondominated Sorting Genetic Algorithm II (NSGA II), known for its efficiency in handling multiobjective optimization problems. By analyzing a bridge subjected to earthquake and flood hazards, the study explores different retrofit materials, columns to be retrofitted, and jacket thicknesses. Three retrofit materials—steel, carbon fiber, and glass fiber composites—are investigated, each with varying strength and unit costs. Nonlinear time history analyses of the bridge, coupled with the optimization algorithm, generate bridge fragility curves, providing crucial information for loss evaluation and resilience estimation. The algorithm searches for parameter values (material properties and jacket thickness) optimizing retrofit costs and bridge resilience. The resulting Pareto near-optimal solutions offer a range of options, each distinct in cost, contribution to resilience enhancement, and design parameters, enabling end-users to select solutions based on their preferences. The study focuses solely on column retrofit as the chosen bridge retrofit option due to its effectiveness in enhancing bridge performance under the multihazard scenario. Other retrofit techniques, such as restrainers at abutments and expansion joints, seismic isolation through bearings, or installation of bigger foundations, are acknowledged but not discussed in detail. The study emphasizes that for the studied bridge model, seismic damage primarily affects bridge columns, making column jacketing the most suitable retrofit measure. This limitation in retrofit scope is attributed to the dominance of flexural damage in the case study bridge.a

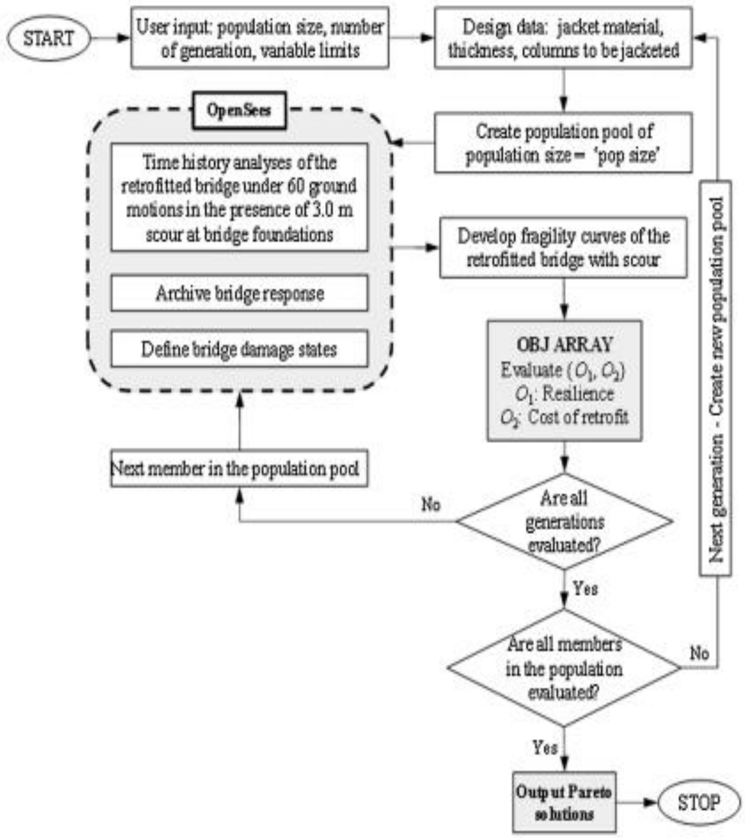


Fig. 1. Flowchart for optimal retrofit design of bridges under the combined effect of earthquake and flood hazards

The results and discussions presented here offer insights into the optimization process and the selection of near-optimal retrofit configurations for highway bridges under multihazard scenarios. Preliminary sensitivity analyses revealed that a population size of 20 and a maximum of 25 generations were sufficient for convergence, thus adopted for the final run. Each retrofit option in the optimization process is characterized by five variables representing the choice of material and jacket thickness for four bridge columns. With the current parameter domain, there are 601 possible combinations for steel and 14617 for each composite material, though some redundancy exists due to bridge symmetry. Throughout the optimization algorithm, fragility curves are generated for each bridge configuration, enabling the calculation of bridge resilience. Results from various generations, including the 1st, 15th, 20th, and 25th, are illustrated in Fig. 8, showcasing the evolution of near-optimal solutions over time. By the 20th generation, Pareto solutions approach convergence, displaying a wide distribution across resilience levels, indicative of a comprehensive search process. Notably, many near-optimal solutions exhibit equal numbers of plies for interior and exterior columns, reflecting the symmetry of the bridge structure.

The final generation's Pareto near-optimal retrofit configurations, presented in Table 2, are ordered by increasing resilience and cost. Solutions demonstrating redundancy due to bridge symmetry are excluded. Interestingly, steel retrofit options are eliminated early in the search process, possibly due to an imbalance in the number of steel versus composite retrofit combinations available for selection. This trend is evident from Fig. 8, where steel solutions gradually give way to composite alternatives as the search progresses. The visualization provided in Fig. 8 offers insights into the evolution of optimal retrofit solutions over generations, particularly highlighting the gradual replacement of steel jacketing solutions by composite alternatives with similar or better resilience at improved costs. Notably, VU27G retrofit options consistently exhibited resilience levels around 65%, closely competing with neighboring TU27C solutions offering marginally higher resilience at similar costs. However, the resilience achieved with VU27G never surpassed 70%, indicating its limited effectiveness in enhancing bridge resilience under multihazard conditions. Among the VU27G retrofit solutions, one economic option stood out, yielding 64.7% resilience at a cost of $22.66 thousand, making it a viable choice compared to neighboring TU27C solutions offering slightly higher resilience at double the cost.

Analysis of the optimal retrofit configurations (Table 2) suggests that interior columns are the weaker components of the bridge, and retrofitting these columns significantly enhances bridge resilience under multihazard conditions. The best-performing solution, yielding nearly 80% resilience, involves 7 plies of TU27C jacketing around interior columns and 1 ply each on exterior columns. Conversely, if cost constraints dictate the retrofit strategy, the VU27G option provides the most optimal solution, maximizing the resilience-to-cost ratio. However, the resilience-to-cost ratio decreases with the use of more composite plies, despite resulting in higher bridge resilience. For instances aiming for approximately 80% resilience, the most economical solution involves 6 TU27C plies for interior columns and none for exterior columns. Each solution presented in Table 2 holds significance, offering distinct retrofit design strategies that can be selected based on specific preferences and constraints. Whether prioritizing maximum resilience, cost-effectiveness, or a balance between the two, the range of solutions provided allows for tailored decision-making in bridge retrofit endeavors.

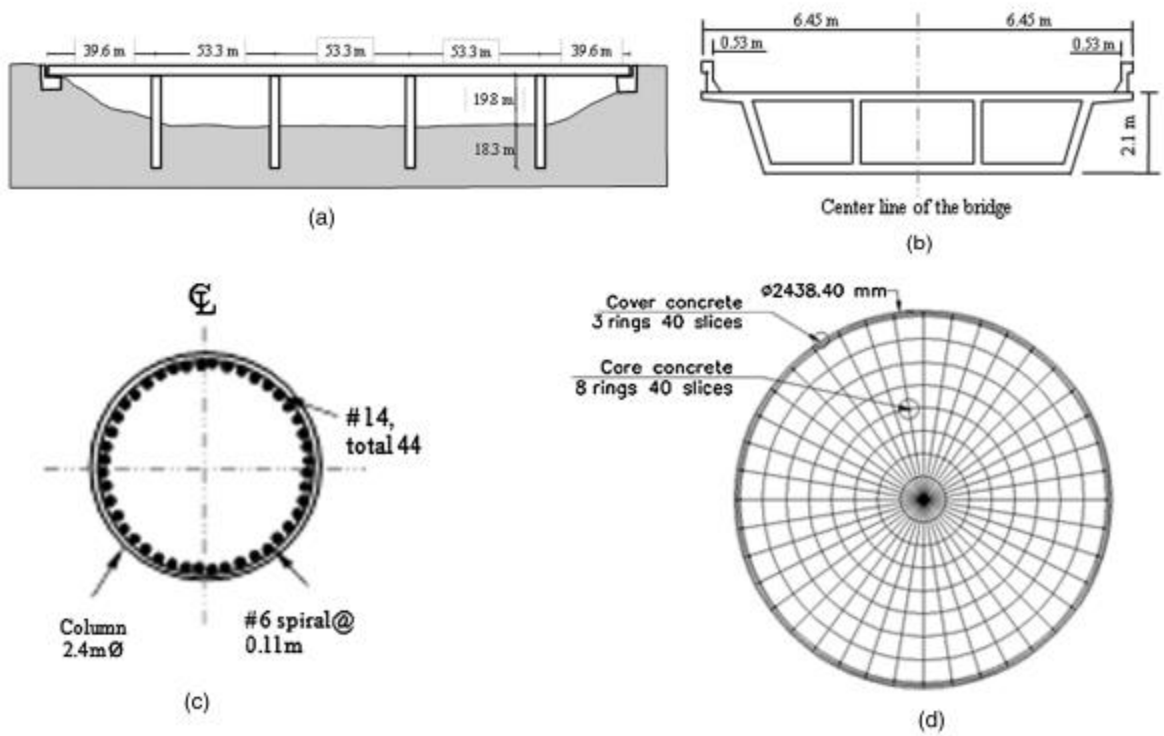


Fig. 4. (a) Schematic of the case study bridge; (b) girder cross section; (c) column cross section; (d) displacement-based fiber element of column cross

section in OpenSees

Results from the optimization run exclusively with steel jacket configurations, as shown in Fig. 9(a), reveal that after 25 generations, the solutions do not form well-defined Pareto fronts due to the dominance of a single solution. The best compromise solution identified achieves 70% resilience of the retrofitted bridge at a cost of $197.50 thousand, marked as D in Fig. 9(a). This configuration entails a 19.05-mm jacket for each of the two interior columns and none for exterior columns. Although higher resilience could potentially be attained by increasing jacket thickness for both interior and exterior columns, the mentioned configuration offers the maximum resilience-to-cost ratio within the given design parameter domain. It's evident from this analysis that steel retrofit options do not emerge as the optimal choice in this scenario.

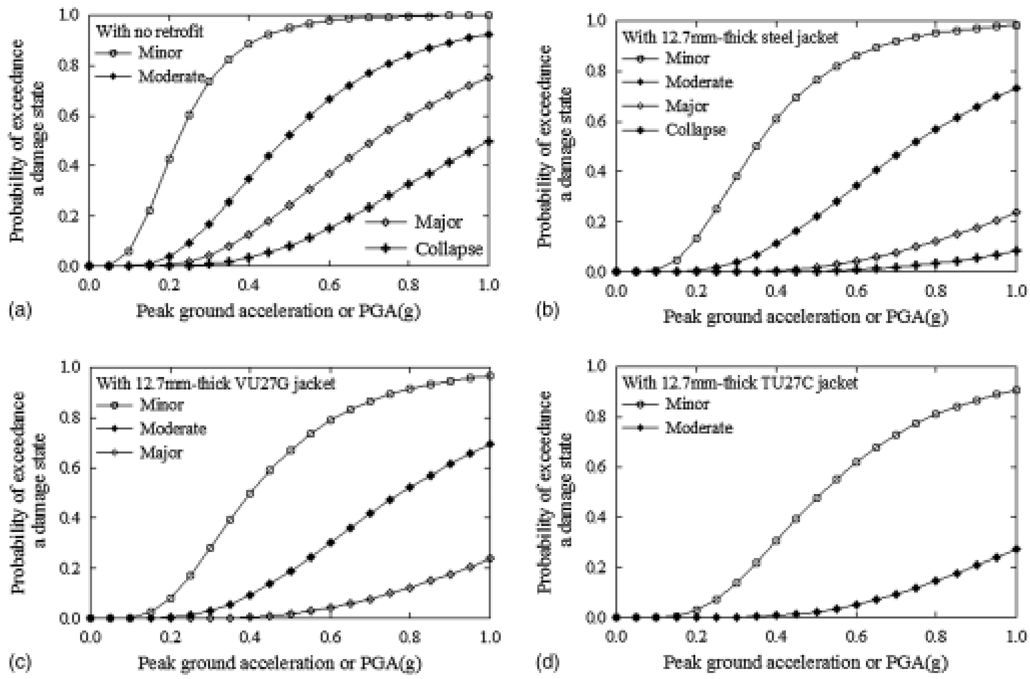
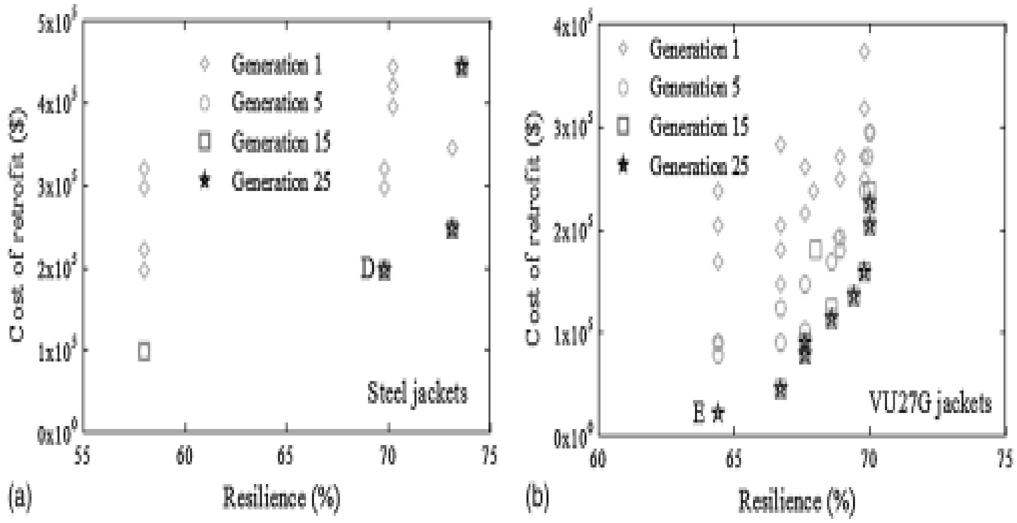


Fig. 6. Fragility curves of the bridge with 3.0-m scour: (a) bridge with no retrofit; (b) retrofitted bridge with 12.7-mm steel jacket; (c) retrofitted bridge

with 12.7-mm VU27G jacket; (d) retrofitted bridge with 12.7-mm TU27C jacket

The Pareto near-optimal solutions obtained at the end of the 25th generation predominantly feature TU27C retrofit configurations, as highlighted in Table 2 and depicted in Fig. 8. However, it's acknowledged that such results might not always align with practical preferences, especially considering the availability of jacketing materials at bridge sites. Given the potential preference for either steel or VU27G jackets due to their easy accessibility, the optimization scope is extended to identify optimal retrofit configurations when jacketing materials are used separately. Additional optimization runs exclusively focusing on steel and VU27G jackets are conducted while keeping the original retrofit design domain unchanged. The only adjustment made is in customizing the number of variables in objective functions based on the specific material used in these additional runs.



The optimization results exclusively focusing on VU27G jackets reveal a clear convergence by the 15th generation, with a well-defined Pareto front observed towards the end of the optimization run. After the 25th generation, nine unique solutions are obtained, each listed in Table 3 in ascending order of resilience. These results underscore the significance of retrofitting interior columns in bolstering the resilience of the bridge. While all optimal solutions offer unique possibilities, one solution stands out as the most optimal when considering the resilience-to-cost ratio, marked as #1 and denoted with E in Fig. 9(b). Remarkably, this same solution also emerged as the optimal choice at the end of the global run, where all three jacketing materials were considered, emphasizing its robustness across different optimization scenarios. earthquake-in-the-presence-of-scour scenarios tend to align, simplifying decision-making processes for such bridges.

	Number of plies for column retrofit						
Solution #	Column 1	Column 2	Column 3	Column 4	Resilience (%)	Cost (×$1,000)	Resilience-to-cost ratio ($\times 10^{-3}$)
1	0	1	1	0	64.7	22.66	2.85
2	0	2	2	0	66.7	45.33	1.47
3	0	3	3	0	67.5	67.99	0.99
4	0	4	4	0	67.6	90.65	0.75
5	0	5	5	0	68.5	113.32	0.60
6	0	6	6	0	69.4	135.98	0.51
7	1	6	6	1	69.8	158.64	0.44
8	1	8	8	1	70.0	203.97	0.34
9	1	9	9	1	70.2	226.63	0.31

To explore the disparity between optimal solutions obtained for earthquake-only and multihazard scenarios (i.e., earthquake following a flood hazard), additional analyses are conducted, maintaining the same seismic hazard at the same bridge location. While a direct comparison between solutions under these two loading conditions isn't feasible due to their inherent differences, general trends emerge from the analysis. Notably, there's a consistent emphasis on retrofitting interior columns over exterior ones to enhance resilience across both scenarios. Additionally, trends related to resilience-to-cost ratio and maximum resilience and cost remain consistent. In instances where flood hazard doesn't significantly affect the seismic vulnerability of a bridge, optimal retrofit strategies for earthquake-only and

2. Conclusion

The study presented in this paper introduces an optimal retrofit design methodology for highway bridges using a multiobjective evolutionary algorithm, specifically the Nondominated Sorting Genetic Algorithm II (NSGA II). The research investigates the impact of various bridge retrofit configurations, namely column jacketing with different materials (steel, TU27C, and VU27G), on bridge performance under the combined effects of earthquake and flood-induced scour. The bridge is assumed to have been pre-exposed to flood hazards resulting in 3.0-m scour at bridge foundations before the earthquake event occurs. The optimization algorithm evaluates bridge resilience under this multihazard condition by exploring all possible retrofit options generated within user-specified bounds of design variables, including jacket material and thickness/number of plies on four columns, while also calculating retrofit costs. The algorithm aims to find optimal retrofit designs by maximizing resilience and minimizing retrofit costs. The study finds that column jacketing proves to be an effective technique in enhancing bridge performance and resilience under the multihazard effect of earthquake and flood-induced scour. Among the three jacketing materials considered, TU27C emerges as the most effective in enhancing bridge resilience. Specifically, applying 12.7-mm (10 plies) TU27C jackets on all bridge columns can result in an 82.6% resilience of the retrofitted bridge, which is notably higher compared to the unretrofitted bridge. The enhancement achieved with TU27C jackets is significantly greater than that obtained with steel and VU27G jackets of the same thickness. The analysis of Pareto near-optimal solutions reveals that TU27C retrofit configurations dominate, with the best-performing solution yielding nearly 80% resilience. This solution involves seven TU27C plies on interior columns and one ply each on exterior columns. Additionally, the study identifies the most optimal solution in terms of resilience-to-cost ratio, which involves the use of one ply each of VU27G on interior columns and none on exterior columns. Notably, a well-defined Pareto front is observed for VU27G retrofit configurations, whereas a similar search exclusively with steel retrofit configurations did not show a well-defined front due to the existence of a dominated solution. Furthermore, the study highlights the higher influence of interior columns compared to exterior ones in enhancing bridge resilience through column jacketing. Near-optimal solutions typically involve an equal number of plies for interior columns and an equal number of plies (or none) for exterior columns, reflecting the symmetry of the bridge structure. Overall, the findings provide valuable insights into optimal retrofit strategies for enhancing bridge resilience under multihazard conditions.

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