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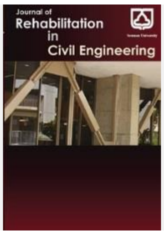

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Seismic Performance and Configuration Assessment of Deficient Steel Frames Equipped with Buckling Restrained Braces

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ABSTRACT

Integrating Buckling Restrained Braces (BRBs) into seismic-resistant structural frameworks presents a sophisticated approach to improving seismic performance. Despite the breadth of research conducted in this area, a noticeable gap persists in comprehending the optimal deployment of BRBs within steel frames that exhibit deficiencies to attain maximal structural efficiency and resilience in seismic events. To address this gap, the present study examines the most efficacious configurations of BRBs. Employing a methodological framework that encompasses the design, modeling, and analysis of twenty-four steel frames demonstrating deficiencies and outfitted with BRBs in varied configurations, this investigation utilizes nonlinear response history analysis as its core analytical tool. This comparative analysis examines eight distinct BRB configurations against a reference scenario devoid of BRBs to identify which most effectively augments seismic resistance. The outcomes derived from the nonlinear response history analysis underscore the pronounced influence of BRB configurations and geometrical variations on critical parameters, including frame weight, base shear, overturning moment, and lateral displacement at the story level. Case C2 was identified as the optimal configuration due to its balanced combination of enhanced performance and weight reduction, making it a reasonable choice for structural efficiency.

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1. Introduction

The susceptibility of steel frames to seismic actions, particularly in earthquake-prone regions, has long been a significant concern in structural engineering. This issue, which can critically undermine the integrity and safety of buildings, has prompted extensive research to understand and mitigate deficient structures. The need for more resilient construction methodologies has led to the innovation of buckling-restrained braces (BRBs), a technology designed to enhance the seismic performance of structures by preventing buckling failure under compressive forces [1]. The concept of BRBs, which emerged in the 1970s and saw its first real-world application in Japan by 1989, represents a critical advancement in seismic-resistant construction [2]. These specialized braces are engineered to allow axial deformation without buckling, thereby maintaining their structural integrity and effectiveness under seismic loading conditions. The distinction between conventional braces and BRBs in terms of buckling behavior is visually represented in Fig. **1**, highlighting the innovative design of BRBs that enables them to resist buckling [3]. This is accomplished with a design featuring a steel core, a buckling restraining mechanism (BRM), and a separation gap, allowing the core to deform axially without influencing the BRM, as shown in Figure 2 [4].

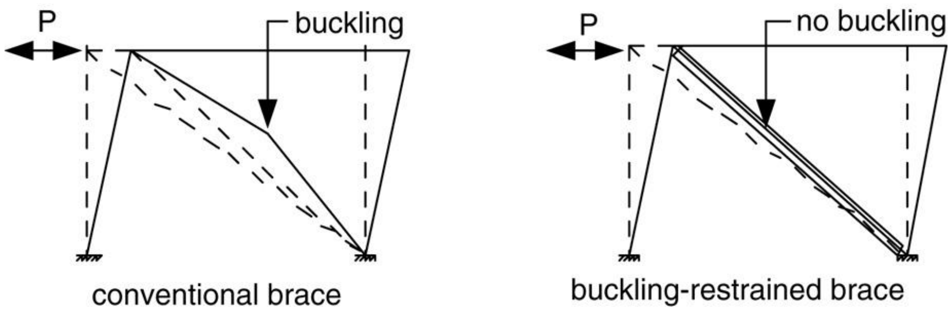


Fig. 1. Buckling behavior of conventional brace and BRB [3].

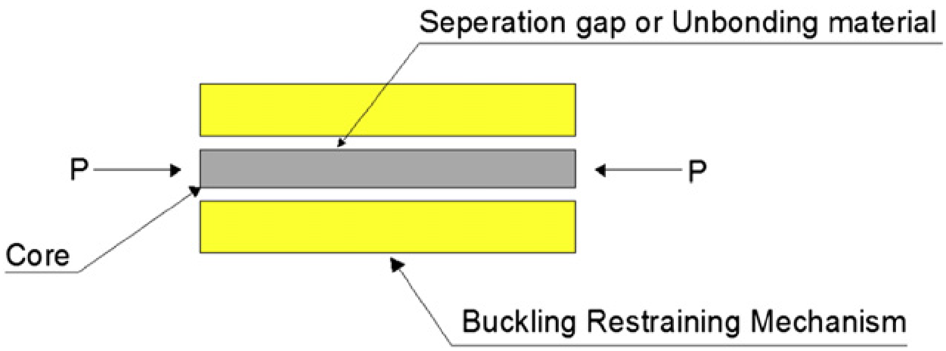


Fig. 2. Typical BRB member components [4].

In recent years, the engineering and scientific community has significantly improved seismic resilience and computational models for various applications as [5–16] . Xie et al. (2024) [17] and Kim et al. (2022) [18] focused on implementing BRBs in mitigating structures against seismic damage. The research highlights the derivation of theoretical equations for tall, reinforced concrete two-column piers, utilizing BRBs to decrease displacement and curvature, thereby controlling seismic response and damage. It emphasizes the utility of BRBs in enhancing the seismic resilience of such structures through numerical simulations and shaking table tests for validation. Qiu et al. (2002) [19] evaluated the seismic performance of shape memory alloy (SMA) BRB systems, comparing them with steel BRB and base isolation systems. They found that SMA BRBs outperform in moderate ground motions, though their performance degrades in stronger ground motions, still retaining superiority over alternatives. Moreover, they discussed Fe-SMA BRBs as superior alternatives to traditional steel BRBs in controlling residual drift ratios, thereby enhancing the seismic resilience of steel frames. This highlights the importance of material innovation in improving seismic performance. Zhao et al. (2022) [14] developed an innovative approach to mitigate frame-to-gusset interaction in BRB-reinforced concrete frames, proposing sliding gusset connections. This method reduced shear force, shifted crack patterns, and lowered gusset stress, leading to an enhanced seismic performance validated by cyclic tests. The damage-control design procedure introduced ensures reliable BRB force transfer and mitigates interaction without the need for post-earthquake replacements. Das et al. (2023) [20] explored seismic retrofitting of torsionally coupled reinforced concrete soft-story buildings using short-yielding core BRBs.

The installation of BRBs was shown to decouple torsionally coupled lateral modes effectively, reducing inter-story drift and enhancing structural performance against lateral responses in soft stories. Recognizing the potential of BRBs to improve the seismic resilience of structures significantly, researchers have explored various aspects of their design, performance, and application. Studies have focused on design procedures for BRB frames that incorporate nonlinear time history analysis and optimization [21], experimental demonstrations of BRBs' ability to sustain both tension and compression [22], and the characterization of BRBs as rigid members that can maintain structural drift within acceptable limits [23]. Furthermore, Al-Sadoon et al. (2020) [24] demonstrated BRBs' versatility and effectiveness in enhancing the structural performance of retrofitting reinforced concrete frames. Hashemi et al. (2022) [25] and Xie et al. (2023) [26] addressed the design and performance of self-centering BRBs (SC-BRBs) under near-fault earthquakes. This research demonstrates the superiority of SC-BRBs in reducing seismic responses and highlights the influence of design load determination methods on their performance, emphasizing the role of innovative design in seismic resilience.

Despite the proven advantages of BRBs and their growing use in earthquake-prone areas, selecting specific shapes and configurations for BRBs remains a subject of ongoing research and debate. The diversity in BRB design, as evidenced by real-life implementations in various shapes and configurations (Figure 3), underscores the need for a deeper understanding of their behavior and the identification of optimal designs for maximizing seismic resilience [27].

This study is motivated by the need to understand the behavior of different BRB configurations and identify the most effective designs for seismic-resisting structures. This study aims to optimize BRB designs, enhancing steel frame constructions' seismic performance and safety. Within the study context, twenty-four deficient steel frames equipped with BRBs of different configurations are designed, modeled, and analyzed through nonlinear response history analysis. Thereafter, the results of the BRB-equipped frames are benchmarked against a control bare structure to understand the system's performance improvements. By addressing the gaps in the current understanding and leveraging the insights gained from both experimental and analytical research, this study seeks to advance the state-of-the-art in earthquake-resistant construction and provide a solid foundation for future innovations in the field.

2.1. History and development of BRB

BRBs are innovative seismic devices designed with a core that primarily yields under axial tension and compression while an outer restraining mechanism prevents the core from buckling. These braces generally consist of a hollow steel section filled with mortar, enclosing a core wrapped in a thin debonding material.

(a) (b) (c)

Fig. 3. Three different BRBs configurations: (a) single diagonal brace [28]; (b) inverted V-brace [29]; (c) X-brace [27].review of buckling restrained braces.

The debonding component, which is the gap between the core and the mortar or within an all-steel restraining configuration, plays a crucial role in the functionality of modern BRBs, as shown in Figure 4. This characteristic is essential because it reduces the transfer of axial forces to the restrainer by providing a low-friction interface and accommodating lateral expansion of the core, a response to Poisson's effect [30]. Consequently, BRBs are known for superior energy dissipation properties, often exceeding other ductile systems' performance. Due to their design, BRBs can act as highly effective hysteretic dampers, showcasing a robust fatigue resistance that can endure multiple design-level seismic events without significant damage.

The application of the BRB, a seismic innovation, is traced back to 1988 [31–33], a development that owed much to Japanese research efforts. Early in the 20th century, the construction focus in Japan was on steel-reinforced concrete (SRC) [34], which was established in skyscraper construction due to its impressive seismic performance. However, although steel-reinforced concrete (SRC) offers a higher load-bearing capacity compared to steel or reinforced concrete alone, its ductility and energy dissipation leave something to be desired.

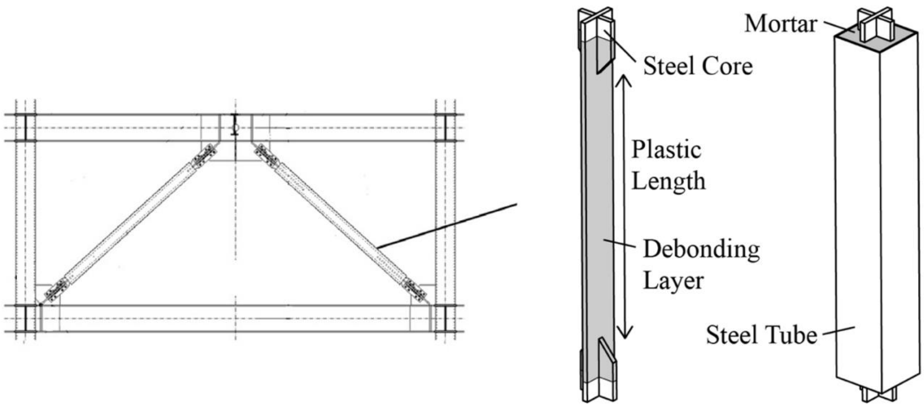


Fig. 4. Concept of buckling-restrained brace [30].

By the late 20th century, Japanese innovators conceived the idea of isolating the steel brace from the concrete encasement to improve the seismic performance of steel-reinforced concrete (SRC) shear walls. This approach can be regarded as a precursor to the modern BRB design [35,36].

Kimura et al. (1976) proposed that [37] this technique be applied directly to the brace to counter the reduced load-bearing capacity, stiffness, ductility, and energy dissipation observed in conventional steel braces under compression. In the subsequent years, Mochizuki and others conducted pivotal research to resolve the global stability challenges of steel braces surrounded by reinforced concrete [35–37]. These concerted research efforts culminated in the practical realization of the first BRBs by Fujimoto and a Nippon Steel Company technical team. The new BRBs were concrete-filled steel tubes embodying practical and theoretical advancements. The team formulated comprehensive theoretical descriptions of the braces' behaviors and corroborated these predictions with experimental evidence. This milestone marked a significant chapter in the evolution of BRBs, leaving a lasting impact on their development and application in seismic-resistant structures.

The utilization of BRBs has seen a marked rise since their inception, with innovations such as the all-steel tube-in-tube variety emerging. By the 1990s, Japan had already incorporated BRBs into roughly 160 buildings. The notion of "damage tolerant structures" came to the forefront in 1992 through the work of [38,39], framing BRBs as elastoplastic dampers within predominantly elastic structural systems. The Architectural Institute of Japan (AIJ) included BRB design guidelines for the first time in 1996, a notable milestone in their integration into engineering practice.

International interest grew, with the first use of BRBs outside Japan at the University of California, Davis, in 1998, and subsequent testing at the University of California, Berkeley, in 2000, as documented by [40] California quickly adopted BRBs, employing them in new constructions and seismic retrofitting projects. By the early 2000s, buckling-restrained braced frames had entered the ANSI/AISC 341-05 [41] Seismic Provisions for Structural Steel Buildings.

During the initial period of global distribution, symposiums held at the Tokyo Institute of Technology played a pivotal role in sharing advancements in building codes, BRB designs, and emerging applications. Over the next decade, the adoption of BRBs spread to various countries, starting with Taiwan in the early 2000s [42], and extending to New Zealand's rebuilding efforts in Christchurch [30]. Nowadays, BRBs are a prominent element in seismic engineering worldwide, with experimental research on these systems being conducted in countries such as the USA, Japan, China, Canada, Italy, New Zealand, Chile, Taiwan, Turkey, Iran, Romania, and others. In a significant contribution to the field, Takeuchi & Wada (2017) [43] have published a state-of-art textbook that is a beneficial resource for the design and practical application of BRBs.

2.2. Categorization of BRBS

In addition to the traditional concrete-filled steel tube BRBs, the development and application of BRBs have evolved to include a diverse range of materials and construction techniques. The classification of BRBs can be generally based on the materials employed or the construction approach of the core brace and the restraining mechanism. The choice of material for the core brace is critical, directly impacting the BRBs' ability to demonstrate the requisite hysteretic behavior and energy dissipation capacity. Essential material properties for optimal BRB performance include high ductility, an appropriate yield point, and sufficient strength and stiffness, all while maintaining a lightweight section [44].

Carbon steel, characterized by a yield strength of approximately 235 MPa, encompasses structural steels like [45–47]. This steel type has been the pillar of steel building structures for decades, favored for its strength, toughness, and weldability. The inception of BRBs heavily relied on this steel, with early models almost universally crafted from it. The cost-effectiveness and ease of processing make carbon steel a sustainable choice for BRB cores, supported by a solid theoretical and practical evidence foundation.

Low-yield-point steel, featuring a yield strength below 235 MPa, demonstrates superior hysteretic behavior, making it highly effective for energy dissipation in seismic applications. In 1989, Nippon Steel Company pioneered a type of low-yield-point steel with a yield strength less than 100 MPa [48], laying the groundwork for the mild steel damper concept. Following this, [49] investigated the use of low-yield-point steel in BRBs, illustrating its potential through practical design examples for seismic control. This material allows for a high-stiffness core brace, which yields relatively low stress levels, enabling early-stage earthquake energy absorption. Further research by [50] through finite element analysis on BRBs made from SLY100 steel and the study by Shi et al. (2018) [51] on an all-steel low-yield-point BRB fabricated from Q195 steel shown in Figure 5, including quasi-static low-cycle reciprocating load tests and finite element (FE) analysis, highlight the ongoing innovation and application of low-yield-point steels in BRB technology.

For over a century, aluminum alloys have been utilized in building construction, primarily in non-structural or auxiliary roles such as curtain walls and partitions, due to their lightweight, ductility, corrosion resistance, and ease of fabrication. However, their application as primary structural components has been limited.

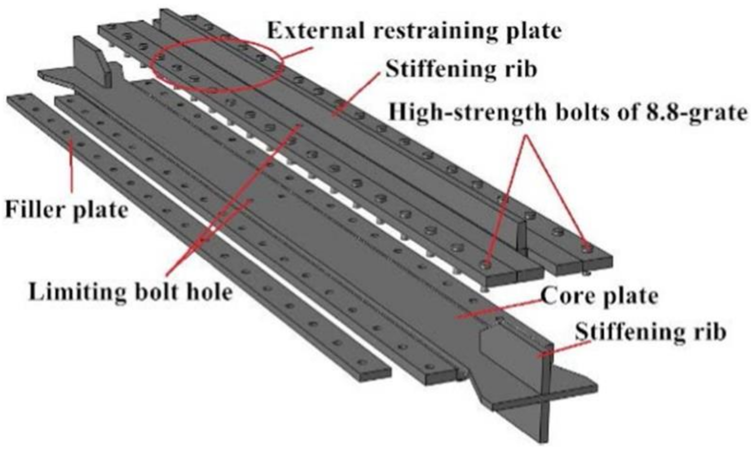


Fig. 5. Diagram of the all-steel assembled LYBR [51].

Recent efforts have explored leveraging aluminum alloys' ductility and their unique behavior under cyclic loading for seismic purposes. When subjected to repeated loads, these materials demonstrate considerable energy dissipation capabilities, making them an attractive choice for the core material in BRBs.

n 2012, Usami et al. [52] conducted research to assess the low-cycle fatigue strength of a high-performance aluminum alloy, with the goal of evaluating its suitability for use in BRBs. Following this, in 2013, Dusicka & Tinker [53] introduced an innovative design for an ultra-lightweight BRB utilizing an aluminum core brace. Their study, which included finite-element simulations, aimed to assess the cyclic performance of these aluminum-based BRBs. Alongside, Wang et al. (2013) [54] conducted low-cycle fatigue tests on extruded aluminum alloy in a BRB context, revealing its potential for stable and consistent hysteretic behavior. Addressing concerns related to corrosion, [55] executed experimental tests on BRBs that combined aluminum alloy and steel cores, validating their effectiveness and durability. This work was further extended by [56], who examined the hysteretic behavior of BRBs with both aluminum and steel cores using numerical simulations and experimental techniques.

3. Research methodology

3.1. Prototype frames

A 10-story deficient steel frame structure was selected as the case study for assessing various BRB configurations in the frame building. The investigated building prototype has 35m ×35m plan dimensions along both orthogonal horizontal axes. The story height of all buildings is 3.5 meters. The structural elements were designed using reinforced concrete with a specified compressive strength of C40 (40 MPa) and deformed high-strength steel with a minimum yield strength of 460 N/mm², in accordance with ASTM-A615M standards. The reference frame is shown in Figure 6. The frame was restrained using various BRB shapes and configurations. Figure 7 presents the twenty-four tested BRB frames, which were then compared with each other and to the reference frame. The BRBs were placed at the center bay of the frame (C cases), the exterior bays (E cases), and both the center and exterior bays (EC cases). These scenarios aim to test the effect of the number of restrained bays and the location of the BRB. All frames were analyzed and designed according to the requirements of the AISC 360-22 [57]. During the design stage, the beams and columns of the frame were optimized using the W-sections of the AISC 360-22 [57], while The BRB section was kept the same across all cases to omit the effect of the BRB section size and solely capture the impact of different configurations, as discussed in Section 2.3. The selection of the deficient steel frame for this study was deliberate to ensure its inadequacy under seismic loading. Initially, the frame was designed solely to meet gravity load requirements, with section sizes and reinforcement details determined accordingly. To verify its deficiency, the frame was subsequently evaluated using the latest Canadian Earthquake Code, where it was found to be noncompliant under lateral forces, thereby confirming its deficient behavior. Several load cases were specified to analyze the structure's response, including dead load, live load, modal load, gravity load, and acceleration load cases. As shown in Figure 8, the methodology and process for the seismic analysis of the 10-story deficient steel frame structure with Buckling-Restrained Braces (BRBs) is detailed.

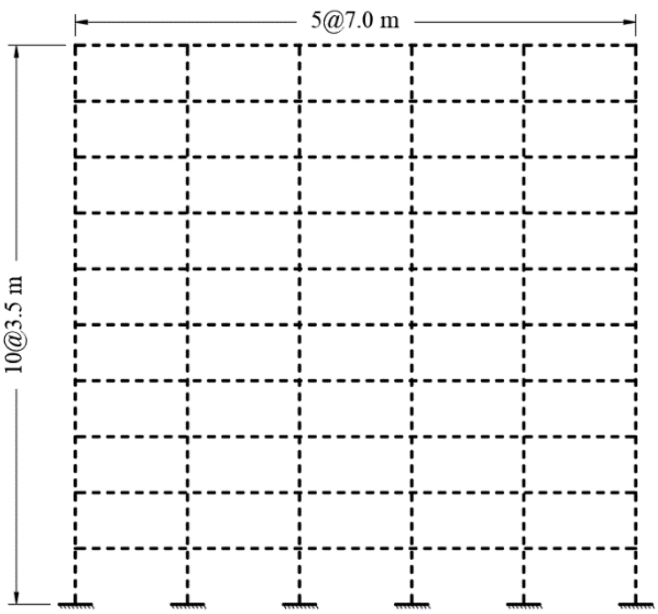
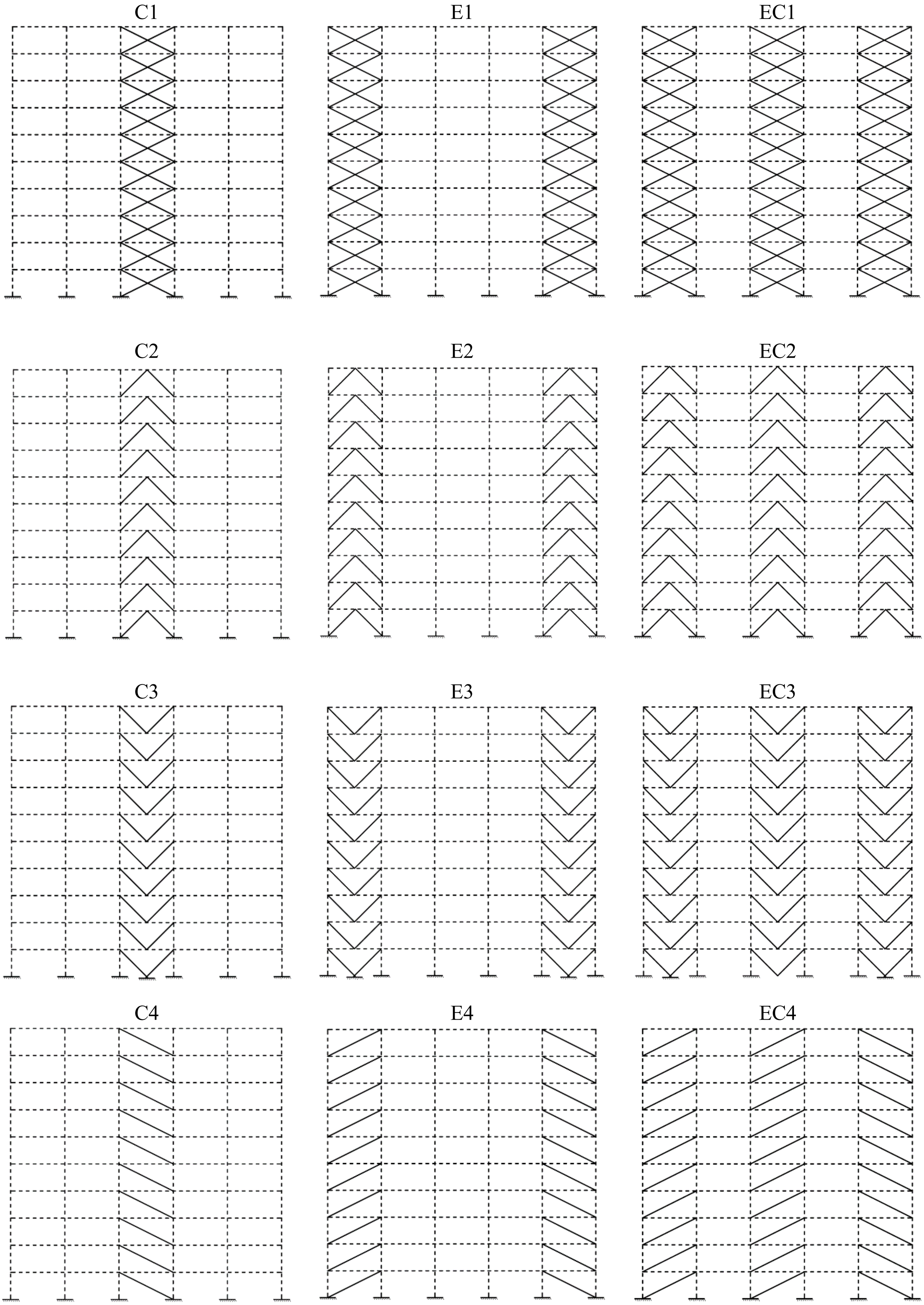


Fig. 6. Reference frame (elevation view).


C1
E1
EC1
C2
E2
EC2
C3
E3
EC3
C4
E4
EC4

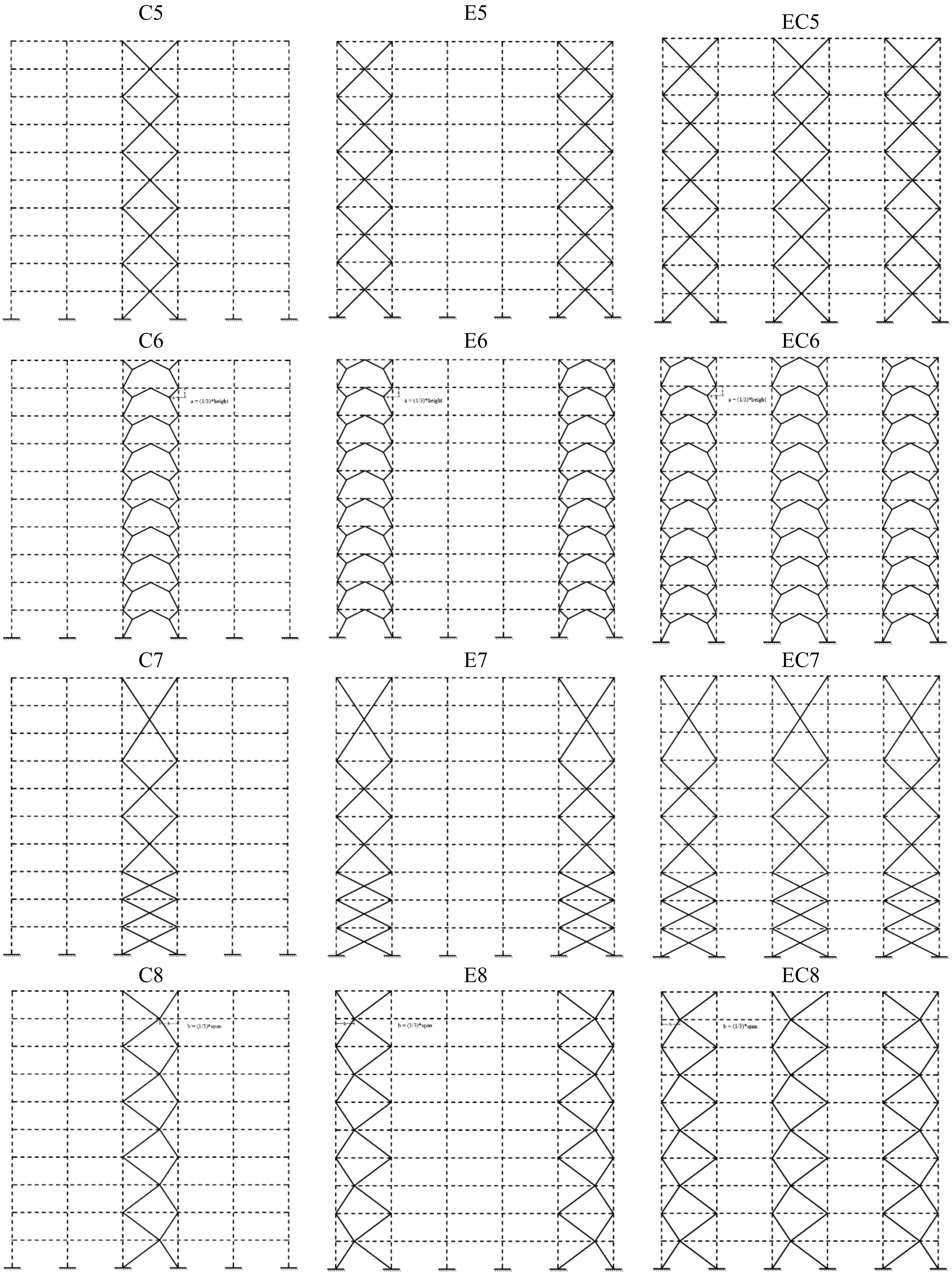


Fig. 7. Configuration of different studied frames equipped with buckling restrained braces.

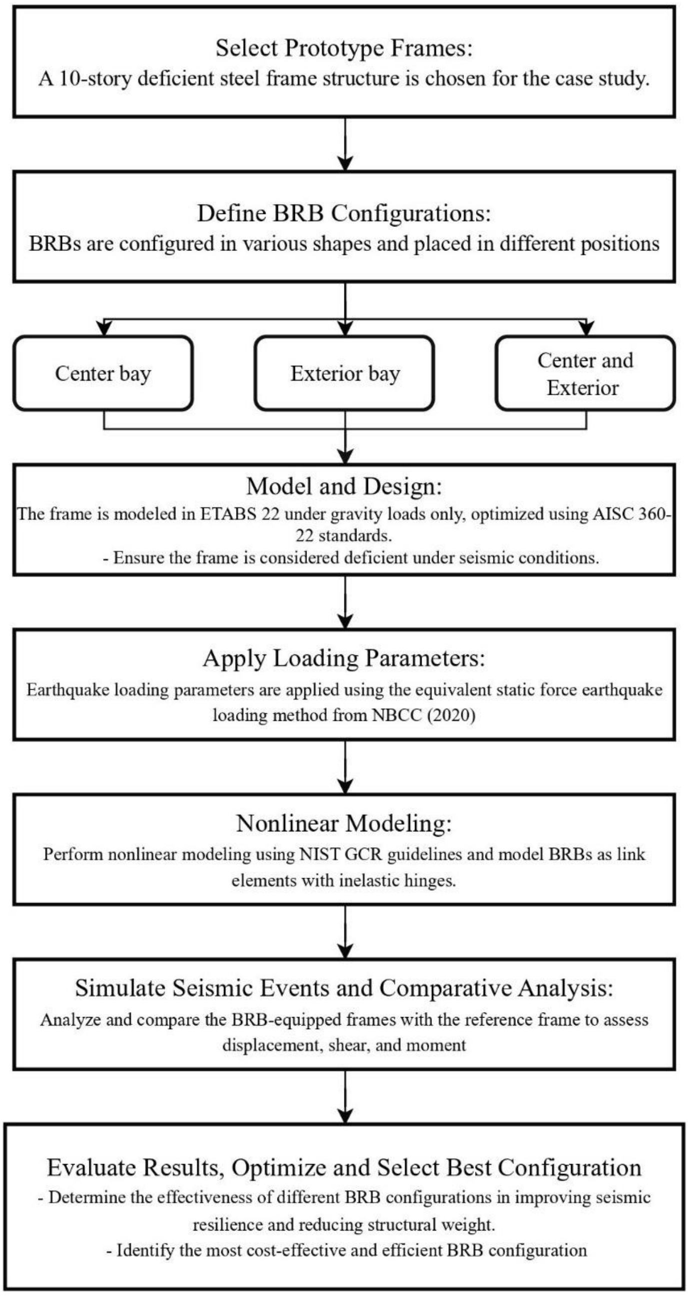


Fig. 7. Methodology and Process for Seismic Analysis of a 10-Story Deficient Steel Frame Structure with Buckling-Restrained Braces (BRBs).

3.2. Preliminary frame design

The frame was modeled as a 3D system in ETABS 21 [58] and designed and optimized under gravity loads only using the AISC 360-22 (2022) requirements to ensure that it will be considered deficient under seismic actions. In this regard, a dead load of 35 kN/m and a live load of 20 kN/m were applied uniformly over all floors' beams in the gravity direction. Thereafter, the beam and column sections were analyzed using the linear elastic approach and applying the provisions of the equivalent lateral force method discussed in NBCC (2020) [59] to confirm the need for seismic enhancement. The parameters and factors used during the lateral load calculations are provided in Table 1.

Table 1. Equivalent static force earthquake loading parameters.

Parameter	PGA	$S_a(0.2)$	$S_a(0.5)$	$S_a(1.0)$	$S_a(2.0)$	$S_a(4.0)$	Site class	F_a	F_v	M_v	R_d	R_o
Unit	/g*	/g	/g	/g	/g	/g	-	-	-	-	-	-
Value	0.40	0.95	0.64	0.33	0.18	0.18	C	1.0	1.0	1.0	5.0	1.5

*g: gravity acceleration = 9.81 m/s^2.

3.3. Modeling of buckling restrained braces

The StartBRB_30.0 section, designed by Star Seismic BRB, is a specialized structural component for engineering and construction projects requiring high seismic performance. This BRB section is characterized by its overall dimensions, performance capabilities, and the unique properties of its yielding core and elastic segments, making it a critical choice for enhancing structural resilience against earthquakes. The selection of the StartBRB_30.0 section was made through an iterative process to ensure that the frame exhibited safe behavior under the equivalent lateral load approach, as per the adopted seismic code. The section's performance capabilities, including its robust yielding core and high stiffness, were critical factors in its selection for achieving the desired seismic performance.Table 2 presents the properties of the BRB section (StarBRB_30.0) used in the analysis and design for all frames.

Table 2. BRB characterization properties.

Property	Overall depth	Overall width	Area of yielding core	Stiffness of elastic segment	Length of yielding core	Length of elastic segment	Tension yield strength	Tension strength	Compression yield strength	Compression strength
Unit	mm	mm	cm^2	kN/m	m	m	kN	kN	kN	kN
Value	406.4	304.8	193.5	5062740.2	4.2672	2.4274	5938.4	7005.9	5871.7	6939.2

The BRB section includes a significant yielding core area of 193.5 cm², specifically designed to undergo plastic deformation under seismic loads, thereby dissipating energy and reducing the forces transmitted to the rest of the structure. The stiffness of its elastic segment is 5062740.2 kN/m, indicating its ability to return to its original shape post-deformation. This elasticity, combined with a yielding core length of 4.2672 m and an elastic segment length of 2.4274 m, ensures flexibility and stability within the structural system. The tension and compression yield strengths are 5938.4 kN and 5871.7 kN, respectively, with maximum tension and compression strengths reaching up to 7005.9 kN and 6939.2 kN. These properties highlight the section's robustness and capacity to sustain significant loads without failure, making the StartBRB_30.0 essential for projects demanding superior seismic performance and safety.

3.4. Nonlinear modeling

Nonlinear modeling of each structure was conducted primarily following the NIST GCR 17 [60] guidelines from the National Institute of Standards and Technology. The nonlinearities in the beam and column sections were introduced into the model using inelastic hinges as defined in ASCE 41-17. Subsequently, the BRB sections were modeled as link elements to accurately capture their nonlinear behavior. Rayleigh damping was employed for the nonlinear direct integration analysis, with a damping ratio of 2.5% at periods equal to 1.5 and 0.25 times the first fundamental mode period, reflecting the inherent damping typically provided for frame structures. Additionally, each beam-column panel zone was simulated to account for its impact on the model's behavior. The analysis also considered the influence of P-delta effects, while soil-structure interaction was neglected by fixing the lower node of each column, thereby eliminating rotation and displacement at the structure's base.

The nonlinearities of the beam and column sections were introduced using a lumped plasticity model, with the inelastic hinges defined according to the ASCE 41 standard. This approach ensured accurate simulation of the nonlinear behavior of these structural elements. Rayleigh damping was then selected for the direct integration analysis, given its proven effectiveness in similar studies. Damping ratios were calculated based on NIST 17 [60] specifications, ensuring comprehensive coverage across a wide range of periods and addressing all modes of vibration.

3.5. Ground motion records

In this study, the structural framework was located in Vancouver, Canada, to evaluate its seismic resistance under extreme loading conditions, combining gravitational and lateral seismic forces with the target spectrum shown in Figure 9. This approach aimed to closely mimic the complex dynamics of real seismic events. Seven real earthquake records, Figure 10, were selected and matched to the target spectrum for a realistic simulation during the nonlinear response history analysis. This rigorous methodology ensures a comprehensive understanding of the framework's behavior under seismic stress, offering valuable insights for enhancing structural design in seismically prone areas.

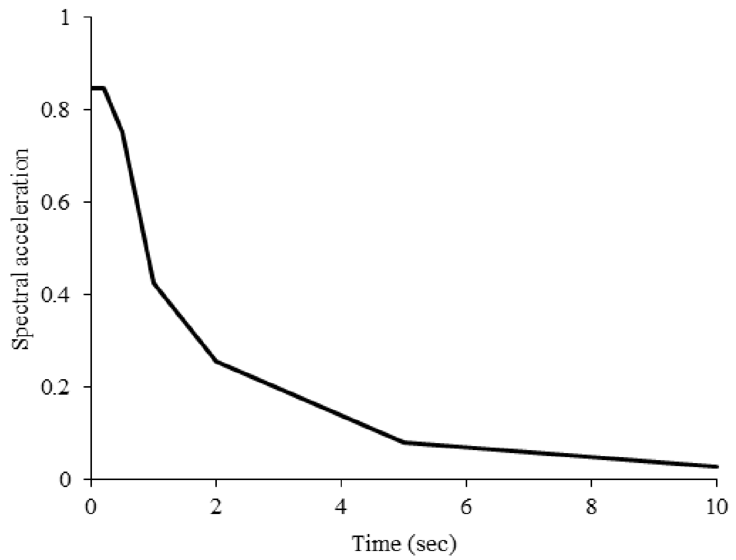


Fig. 8. Target acceleration response spectrum.

4. Results and discussion

The comparative analysis of BRB-equipped steel frames reveals significant insights into optimizing frame configuration, weight, and lateral displacement at the top story. Table 3 benchmarks story displacement for various BRB configurations under seismic load, categorized by their placement within the structure. Central placement (C1-C8) shows improved performance in terms of story displacement with up to 68.7% roof response enhancement in the C2 case. End configurations (E1-E8) generally perform better than the central case with lower displacement values. The best end case is E2, which has reached a 73.9% reduction in the roof displacement compared to the reference case.

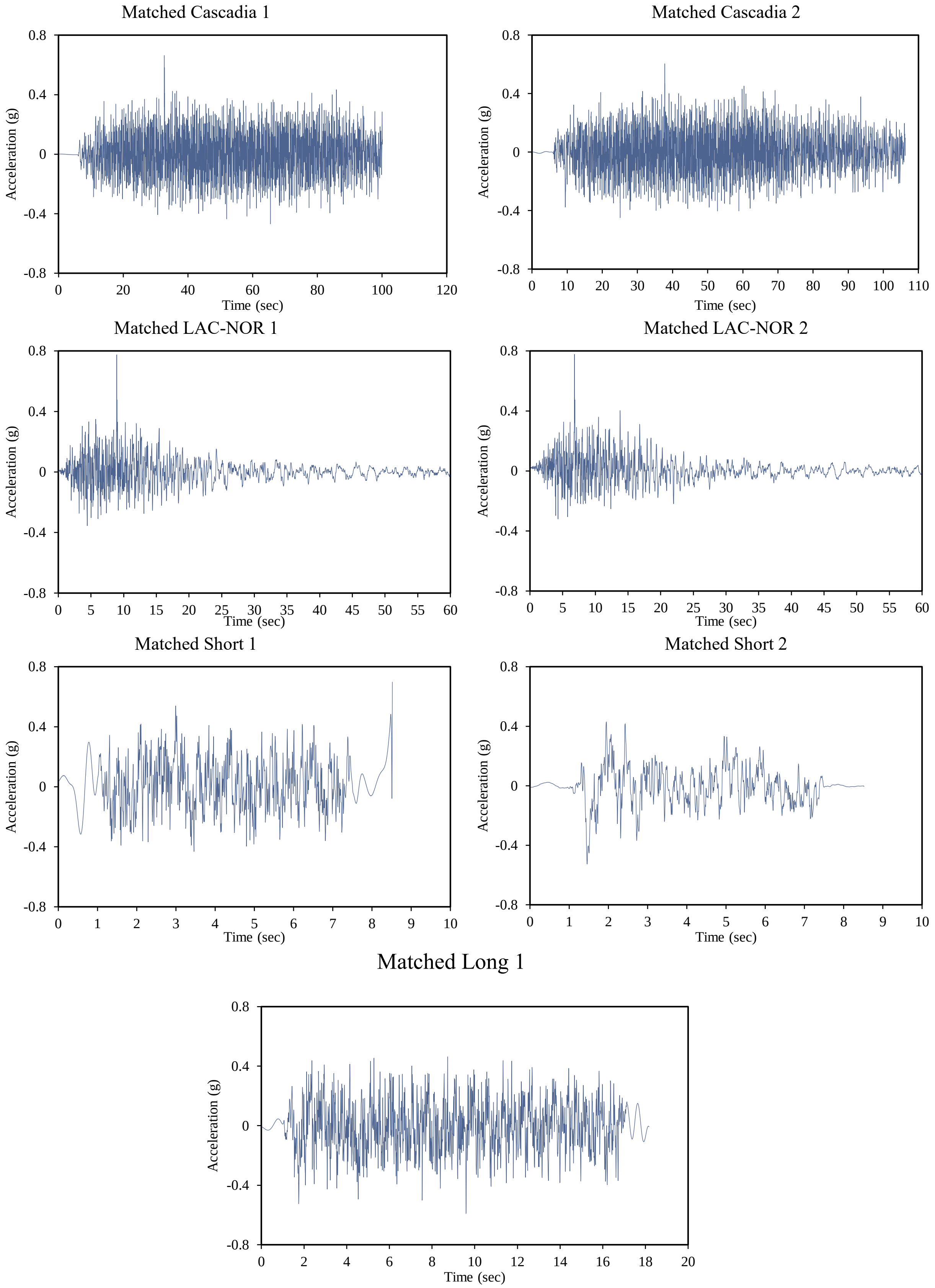


Fig. 9. Applied time-history function.

Combined placements (EC1-EC8) offer the best displacement profile, with EC2 demonstrating the best seismic force mitigation, recording the lowest roof story displacement at 83.5%. This data underlines the influence of BRB placement on seismic energy management within a frame, with EC configurations emerging as effective in reducing displacement, thus enhancing structural resilience. Figure 11 presents a comprehensive comparative analysis, comparing various Buckling-Restrained Brace (BRB) configurations against a control model across four critical metrics: frame weight, roof displacement, base shear, and base overturning moment. Specifically, sub-figure (a) shows the variations in structural frame weight, offering insights into the material efficiency of each BRB case compared to the control. Sub-figure (b) delineates the roof displacement under seismic or dynamic loading conditions, serving as a proxy for the overall deformability and resilience of the structure. Sub-figure (c) quantitatively.

Table 3. Benchmarking story displacement of the investigated cases against the reference frame (Unit: %).

Story Number	Case Number							
	C1	C2	C3	C4	C5	C6	C7	C8
10	66.8	68.7	61.2	58.9	65.0	56.0	65.5	64.1
9	68.3	69.9	62.6	59.6	66.4	55.8	65.8	65.6
8	70.1	71.6	64.3	60.8	68.4	56.3	68.0	67.8
7	72.1	73.4	66.2	62.1	70.5	57.1	71.4	69.9
6	74.0	75.2	67.8	63.1	72.4	57.2	73.7	71.8
5	75.9	77.1	69.5	64.1	74.8	57.6	75.9	74.1
4	77.9	78.9	70.9	64.7	76.6	57.8	78.4	75.9
3	80.1	81.2	72.2	65.1	79.7	58.1	80.3	78.5
2	81.6	82.9	72.4	63.6	80.9	56.8	81.7	78.2
1	80.0	81.9	66.2	54.4	84.7	49.7	80.5	82.2
Base	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Story Number	Case Number							
	E1	E2	E3	E4	E5	E6	E7	E8
10	70.8	73.9	67.1	66.8	68.0	64.7	70.1	69.5
9	72.5	75.4	68.6	67.9	69.8	65.2	70.8	71.1
8	74.4	77.1	70.3	69.3	71.9	66.2	73.1	73.1
7	76.4	79.0	72.0	70.8	74.3	67.5	76.3	75.4
6	78.3	80.7	73.6	72.1	76.2	68.6	78.7	77.1
5	80.3	82.7	75.2	73.5	78.9	69.8	80.7	79.6
4	82.3	84.7	76.7	74.6	80.7	70.6	83.3	81.0
3	84.5	86.9	78.2	75.8	84.2	71.7	85.0	84.4
2	86.3	88.8	78.7	75.6	85.3	71.1	86.7	84.2
1	86.5	89.5	74.8	70.2	91.7	64.6	86.9	89.2
Base	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Story Number	Case Number							
	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8
10	81.5	83.5	79.1	78.3	80.5	79.8	80.6	79.9
9	82.4	84.3	79.8	78.8	81.4	80.1	80.7	80.9
8	83.5	85.3	80.7	79.4	82.5	80.8	82.2	82.0
7	84.7	86.4	81.7	80.2	83.8	81.6	84.3	83.4
6	85.8	87.4	82.5	80.8	84.8	82.4	85.8	84.3
5	87.0	88.6	83.4	81.4	86.4	83.3	86.9	86.0
4	88.2	89.7	84.1	81.8	87.3	84.1	88.8	86.6
3	89.5	91.1	84.9	82.2	89.6	85.0	89.7	89.0
2	90.7	92.4	84.9	81.3	90.1	85.4	90.8	88.5
1	90.8	93.3	81.9	75.4	95.2	83.6	91.0	94.7
Base	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Low Efficiency ⟷ High Efficiency								

assesses the base shear, which is indicative of the lateral force resistance capacity of the structure, thereby reflecting on the efficacy of the BRB implementations in enhancing lateral stiffness. Lastly, sub-figure (d) addresses the base overturning moment, a critical parameter that highlights the rotational resistance offered by the structure under lateral loads. These comparisons underscore the impact of BRB integration on structural performance, providing a holistic view of its benefits and limitations in seismic retrofitting or design scenarios.

Figure 11(a) delineates a pronounced increase in frame weight concomitant with the addition of braced bays. Remarkably, Case C4 is distinguished by achieving the minimal optimized frame weight, quantified at approximately 850 kN. This result elucidates an optimization approach that potentially reduces material expenditures while preserving structural integrity. In contrast, Figure 11(b) elucidates that Case EC2 is characterized by the minimal roof story lateral displacement, measured at approximately 12 mm. This diminution in displacement indicates a system with enhanced stiffness, which may ameliorate damage susceptibility during seismic activities. Nonetheless, this improved performance is accompanied by an augmented frame weight, which may influence foundation design requisites and escalate overall construction costs.

As represented by Cases C1, E1, and EC1, traditional X-brace configurations failed to meet the benchmarks for optimized structural weight, indicating a potential reevaluation of conventional bracing strategies. Intriguingly, Case C5, which employs bracing in a singular center bay, exhibits performance on par with Case E5, where bracing is applied to two external bays in terms of top story displacement. Moreover, Case C5 is advantageous in economic efficiency owing to its lesser weight, underscoring the efficacy of strategic Buckling-Restrained Braces (BRB) placement. Figures 11(c) and 11(d) present trends analogous to those observed in Figures 11(a), corroborating the similar influence of BRB configuration on the structural behavior of steel frames.

This analysis suggests that the strategic placement and configuration of BRBs play a pivotal role in achieving optimized structural designs that balance material cost savings with enhanced seismic performance. The findings underscore the necessity for a nuanced understanding of bracing effects on frame behavior, paving the way for innovative design strategies in seismic-resistant construction.

In addition, a comparative analysis delineating the performance of optimal BRB implementations against the control model was carried out to evaluate the efficacy of Buckling Restrained Braces (BRBs) within seismic retrofitting strategies, as shown in Figure 12. Critical metrics for this comparison include: (a) Story displacement, which quantifies lateral movement of each floor level, thereby gauging the structure's ability to withstand seismic forces without significant displacement; (b) Interstory drift ratio, a critical measure of relative displacement between successive stories, indicative of the building's deformation capacity and directly correlating with damage potential during seismic events; (c) Story shear, representing the shear force distribution across individual stories, providing insight into the structural demand and the effectiveness of BRBs in redistributing these forces to mitigate potential shear-related failures; and (d) Overturning moment, assessing the moment forces that attempt to rotate the structure about its base, a key parameter in understanding how BRBs contribute to overall structural stability by counteracting these moments. This comparative framework highlights BRB systems' resilience and performance enhancements and furnishes a comprehensive understanding of their role in seismic risk mitigation for reinforced concrete structures.

Case EC2 emerges as the superior choice in the context of story displacements and interstory drift ratio, offering the most effective performance across all stories when juxtaposed against alternative configurations. However, considering the discussions on structural weight implications, Case C2 is the optimal configuration. This conclusion is drawn from its ability to balance enhanced performance and weight reduction, marking it as a pragmatic choice for structural efficiency.

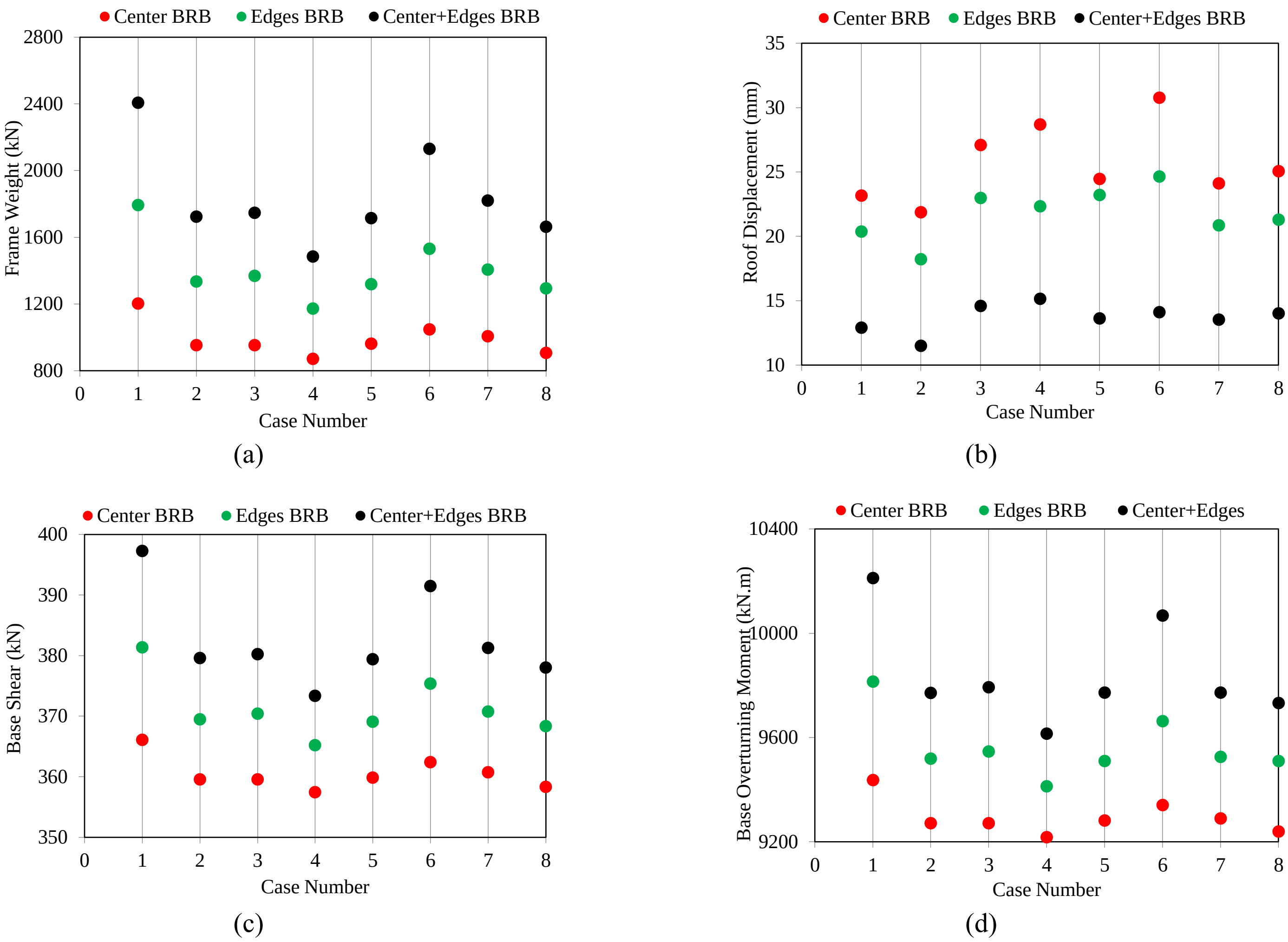


Fig. 10. Comparison of different BRB cases against the control one: (a) Frame weight; (b) Roof displacement, (c) Base shear, and (d) Base overturning moment.

The story shears across different framing configurations, illustrating that, despite minor variations, all frames exhibit comparably similar shear values. Notably, the control frame has the lowest shear forces and, consequently, base overturning moments, attributable to the fact that Buckling-Restrained Braces (BRBs) enhance structural stiffness in other cases, thereby attracting higher lateral loads. This analysis underscores the importance of evaluating structural systems not solely based on individual performance metrics but by considering the interplay between structural stiffness, load distribution, and overall mass.

5. Conclusion

This study thoroughly examined the seismic performance of buckling-restrained braces (BRBs) within steel frames, concluding in selecting an optimal design from eight distinct BRB configurations of twenty-four evaluated models against a reference scenario. Analytical methods determined that the case featuring bracing in the center bay (herein referenced C2) represents an ideal equilibrium between minimizing structural weight and controlling lateral movement, thus emerging as the most cost-effective and efficient design solution. Case C2 notably reduced structural weight while ensuring roof story displacements remained with lesser displacements.

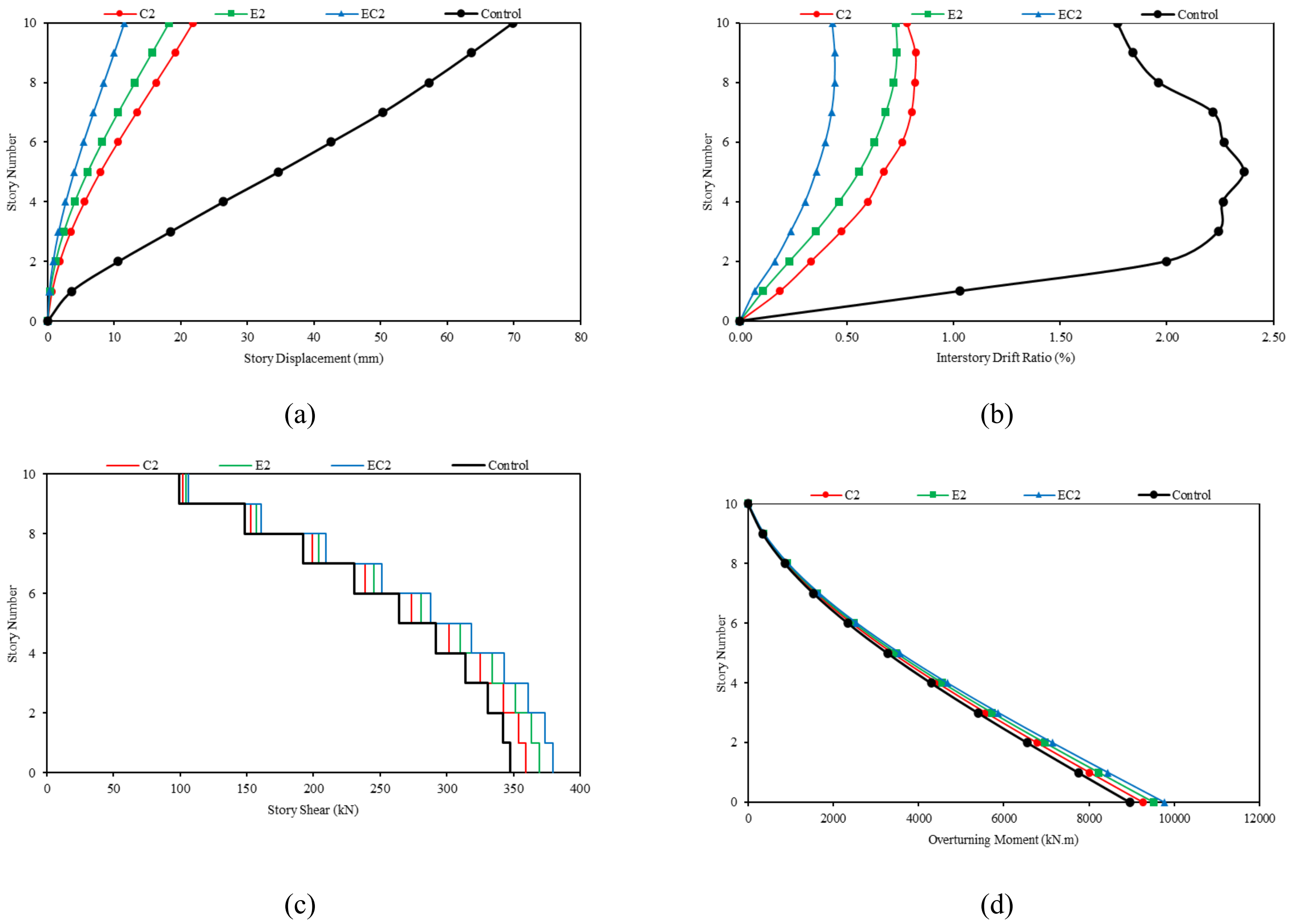


Fig. 11. Comparison of the BRB performing cases against the control one: (a) Story displacement; (b) Interstory drift ratio; (c) story shear; (d) overturning moment.

This configuration outperforms traditional X-brace designs in terms of both efficiency and operational effectiveness, as evidenced by the comparative analysis. The investigation further analyzes the story shears across various framing configurations, revealing that, despite slight variations, all frames exhibit relatively comparable shear values. The control frame, devoid of BRBs, displays the lowest shear forces and minimal base overturning moments. This is attributed to the enhancement of structural stiffness by the BRBs in other configurations, which in turn attracts higher lateral loads.

To bridge the gap between theoretical analysis and practical application, future research should explore how different BRB configurations interact with various material properties and assess their durability under diverse seismic conditions. Such comprehensive studies will enhance understanding of the durability and safety of constructions in earthquake-prone regions. While the lumped plastic hinge model used in this study offers simplicity and is widely adopted, it may not fully capture the geometric and material nonlinearity under large deformations as effectively as distributed fiber hinges. This limitation should be acknowledged, and future studies may benefit from using fiber models for more accurate simulations. Additionally, soil-structure interaction was not included in this analysis to reflect common design office practices, where computational efficiency is prioritized. However, incorporating soil-structure interaction effects in future studies could provide a more comprehensive understanding of the structure's behavior under seismic loading. Furthermore, while this study employed 3D modeling for structural analysis, it is recommended that future research consider 3D modeling to gain more detailed insights into structural behavior. Although currently computationally demanding, 3D analysis could offer a more thorough understanding of the effects of seismic forces on complex structural systems.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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