International Journal of Advanced Engineering and Management Research

Vol. 10, No. 05; 2025

ISSN: 2456-3676

Comparison of the Behavior and Cost of Moment Frame Structures, X-bracing, and Inverted V-bracing for Low-story Building

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doi.org/10.51505/ijaemr.2025.1417 URL: http://dx.doi.org/10.51505/ijaemr.2025.1417

Received: Oct 10, 2025 Accepted: Oct 21, 2025 Online Published: Oct 28, 2025

Abstract

This research compares the efficiency of three steel structural systems, namely moment frame, X-bracing, and inverted-V bracing, in a four-story school building in a high earthquake zone. Analysis is carried out using linear static and dynamic spectrum responses based on applicable earthquake load provisions to determine the structure's response to earthquakes. Cost estimates focus on the main components of the structure, namely columns, beams, and braces. The results indicate that all systems meet the safe limits of deflections and demand-to-capacity ratio (D/C < 1.0). The maximum deflections were recorded at 31.32 mm for the moment-frame, 21.50 mm for the X-brace, and 21.39 mm for the inverted-V bracing, indicating that the bracing system is more effective in reducing deflection. In terms of materials, the moment-frame requires 108 tons of steel, X-bracing 94.3 tons, and inverted-V bracing 89.2 tons. Cost estimates indicate savings of 13.1% for Bracing-X and 17.8% for Bracing Inverted-V. Even though the inverted-V bracing system has the potential to disrupt spatial planning, this system remains the most technically and economically efficient for educational buildings in high seismic areas.

Keywords: Steel structures, bracing systems, seismic zones, material efficiency.

1. Introduction

Designing multi-story building structures, cost efficiency is a key consideration influencing design decisions besides safety and standard. Four-story buildings, often used for commercial, educational, and residential purposes, require structural systems capable of resisting not only gravitational loads but also lateral forces such as earthquakes and wind. Selecting the right structural system directly impacts material requirements, construction complexity, and total construction costs (Apriani & Rahmat, 2020). Therefore, analyzing various alternative structural systems is crucial to produce a technically and economically optimal design.

The most common structural system used in steel construction is the moment frame. Moment frame systems offer spatial flexibility and ease of interior design but tend to require larger steel elements to resist lateral forces (Dorri, Hooman Ghasemi, & Jalilkhani, 2023; Wiryadi, Tubuh, Wirawan, & Diangga, 2024). Unlike X-bracing and inverted-V bracing systems, which provide additional stiffness through diagonal elements, such systems can increase structural stability and reduce the dimensions of the main elements (Al-Safi, Alameri, Wasel, & Al-kadasi, 2021; Kianmehr, 2021; Meena, Awadhiya, Paswan, & Jayant, 2021; Safarizki, Kristiawan, & Basuki, 2013). However, the bracing configuration can affect the spatial layout and aesthetics of the building, so its selection must consider both functional and architectural aspects. From a cost perspective, each structural system has different implications for the volume and type of steel required.

Moment-frame systems tend to require larger steel profiles and a greater quantity to achieve a level of stiffness equivalent to that of braced systems (Gusella, Orlando, & Peterman, 2019; Hernández-Montes & Aschheim, 2019; Nikellis, Sett, & Whittaker, 2019). This fact is due to the absence of lateral stiffeners, allowing lateral loads to be fully borne by the main frame elements. Conversely, bracing systems such as the X-frame and inverted V-frame can increase structural stiffness through diagonal elements, thereby reducing the need for steel in the main columns and beams (Hassan & Al-Wazni, 2023; Malik & Sutrisno, 2023). However, the addition of these diagonal elements also requires additional material, both in terms of the quantity and type of steel profiles used (Rahimi & Maheri, 2020). These differences in configuration result in variations in the total structural weight, connection complexity, and force distribution efficiency. Furthermore, the unit price of the steel materials used in each system also influences the overall project cost estimate.

This article presents a comparative analysis of three steel structural systems: the moment frame, the X-brace frame, and the inverted V-brace frame, focusing on estimating the material costs for a four-story building. While previous studies have addressed the technical performance and stiffness of each system, studies specifically linking structural configuration to the cost efficiency of steel materials in multi-story buildings are limited, particularly in the context of four-story buildings commonly used in Indonesia. This study aims to fill this gap by presenting quantitative data and comparative analysis that can assist consultans and contractors in selecting the most economical structural system without compromising safety, functionality, and ease of implementation. The study's results are expected to serve as a practical reference for making sustainable design decisions, adapting to standard conditions, and aligning with the principles of structural efficiency.

2. Method

The object of study in this research is a four-story school building designed as an educational facility in an area with a high level of seismic activity, namely Bali Province. This building has a floor height of 3.6 meters and is categorized in risk design category (RDC) IV, in accordance with Indonesian Earthquake Code, which stipulates those educational buildings must remain functional after an earthquake (BSN, 2019). Therefore, the importance factor used in the analysis is 1.5. The loading on the structure follows the provisions of Indonesian Code for gravity loads,

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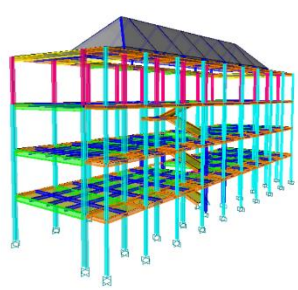
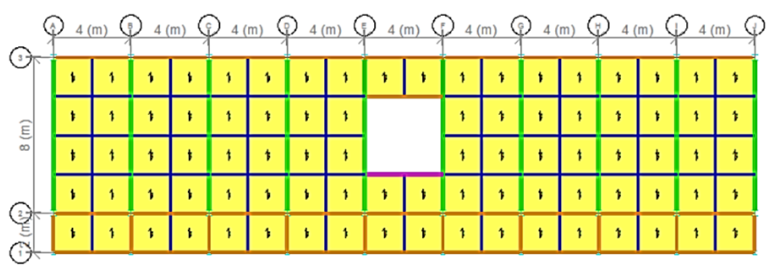
ISSN: 2456-3676

which include dead loads, live loads, finishing loads, and installations (BSN, 2020). Meanwhile, the lateral load, in the form of an earthquake load, was determined based on Indonesian Earthquake Code (BSN, 2019), with seismic parameters referring to the 2021 Indonesian Earthquake Map. The spectral acceleration values used were Ss = 0.945 for a 0.2-second period and S1 = 0.3976 for a 1-second period. The site class was assigned Class D, reflecting moderate soil conditions with the potential for significant earthquake amplification.

The main structure of the building uses profiled steel, with I-Wide Flange (IWF) and H-beam beam and column elements, in accordance with the design requirements in Indonesian Steel Code (BSN, 2020b). The design capacity is determined based on the load combination that provides the maximum condition for each structural element, as presented in Table 1. This study compared three different structural systems: an open frame (moment frame), an X-bracing system, and an inverted V-bracing system. These three models were analyzed to assess the efficiency of steel material use and structural performance in facing earthquake loads. The modeled structure is only the superstructure with fixed support at the ground floor level. The contribution of the floor slab stiffness to the beams is neglected so that the frame stiffness is purely based on the stiffness of the beams and columns and their connections. This simplification allows for a more straightforward analysis of the frame's behavior under load. Structural analysis was conducted using a linear static and dynamic response spectrum approach, with the assistance of structural analysis software. The primary objective of this analysis is to evaluate the steel quantities and weight requirements of each structural system, as well as to estimate the cost based on the total steel weight multiplied by the unit price of the material. The results of this analysis are expected to provide recommendations for the most technically and economically efficient structural system for educational buildings in high-seismic zones.

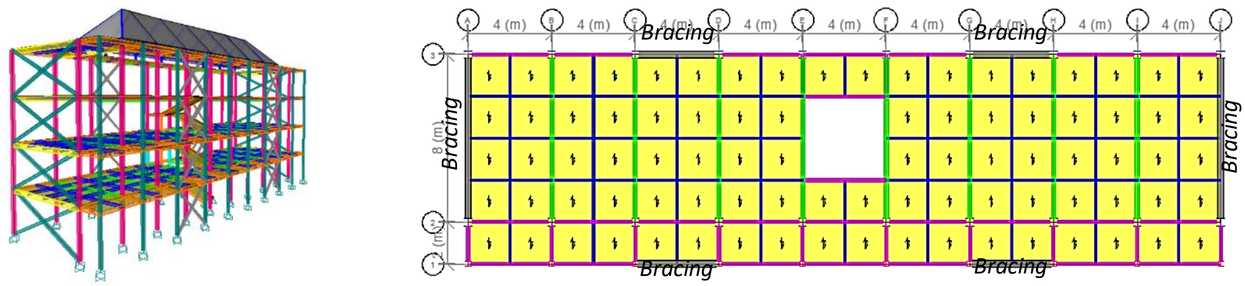


3D



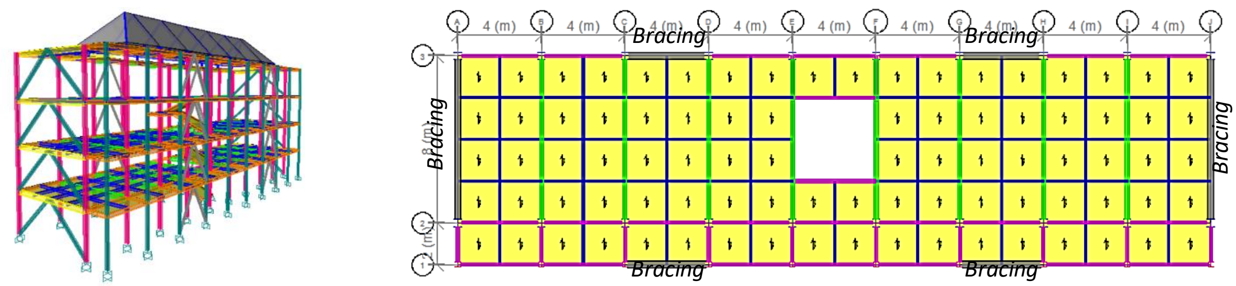
Plan

Figure 1. Moment frame structure



3D *Plan*

Figure 2. X-bracing structure



3D *Denah*

Figure 3. Inverted-V bracing structure

Table 1. Load Combinations

Number	**Combination**
1	1.4D
2	1,2D + 1,6L + 0,5 (Lr or R)
3	1,2D + 1,6(Lr or R) + L
4	1,2D + E + L
5	0,9D + E

Load annotation:
D : Dead, L : Live, Lr : Roof Live E : Earthquake, R : Rain

3. Results and Discussion

3.1 Maximum Lateral Deflection

The results of the dynamic response spectra analysis indicate that the structural system with the moment frame configuration exhibits the largest maximum deflection when compared to the other two systems analyzed. In the four-story building under consideration, the maximum allowable deflection is 1% of the total floor height (about 144 mm) for seismic design category IV. The maximum lateral deflections recorded were 31.32 mm for the moment frame system, 24.98 mm for the X-braced system, and 24.44 mm for the inverted V-braced system. These

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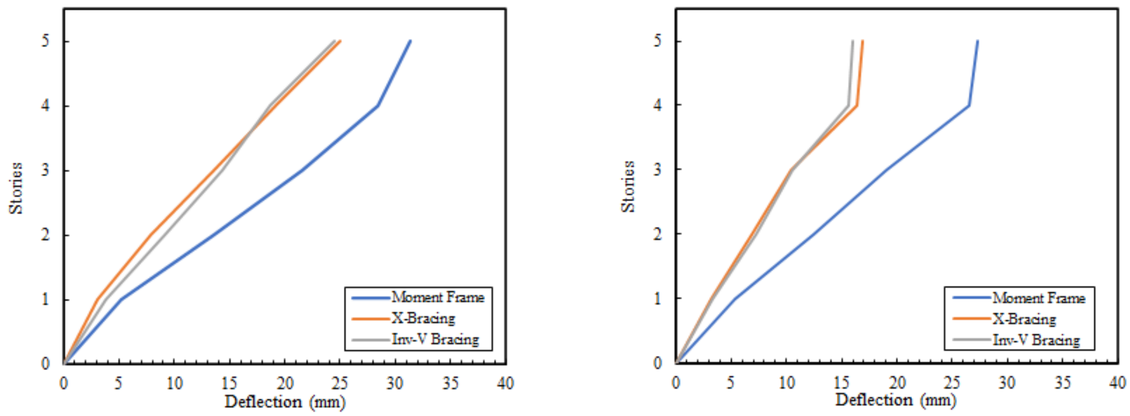
values suggest that the bracing system significantly contributes to the lateral stiffness of the building, thereby effectively minimizing the displacement resulting from the design earthquake.



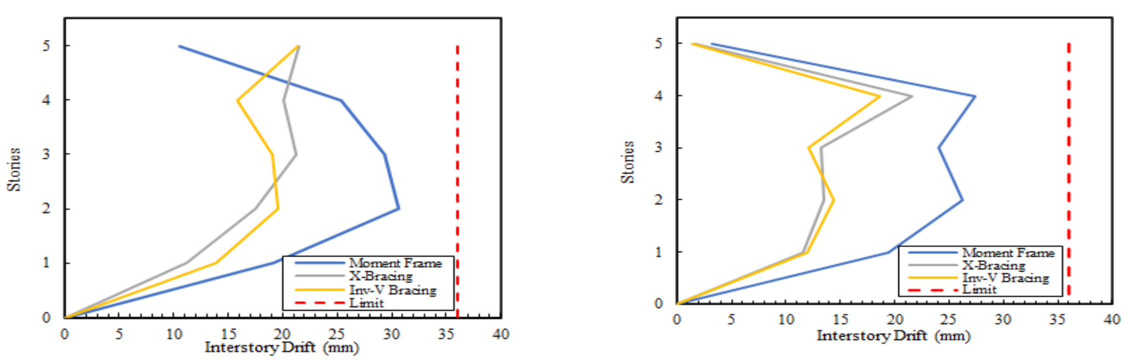
X-Direction *Y-Direction*

Figure 4. Maximum story deflection

3.2 Inter-story Drift

Inter-story drift is an important indicator in assessing the comfort and safety of a building against lateral deflection. Based on the analysis results, the moment frame system showed the highest inter-story drift value, namely 30.59 mm, approaching the maximum limit permitted by SNI 1726 2019 for KDR IV buildings (BSN, 2019). The X-bracing system produced a drift of 21.50 mm, while the inverted V system was 21.39 mm. Both bracing systems are still within safe limits and show better performance in controlling inter-story deflection. The inter-story drift deflection (δ_i) is calculated based on the elastic lateral deflection due to the design earthquake (δ_e), the deflection magnification factor (C_d), and the priority factor (I_e), as in Equation (1). Meanwhile, the permissible inter-story drift is taken as 1% of the height between the stories reviewed based on the risk design category IV.

$$\delta_i = \delta_e \; (C_d/I_e) \quad (1)$$



X-Direction *Y-Direction*

Figure 5. Inter-story drift

3.3 Demand-to-Capacity (D/C) Ratio

The Demand-to-Capacity (D/C) ratio is an important indicator in evaluating steel structural elements, as it indicates the magnitude of the applied load (demand) compared to the element's maximum capacity (capacity). A D/C value close to 1.0 indicates that the element is operating near its capacity limit, while a lower value indicates that the element still has sufficient reserve capacity. In moment-frame structures, D/C ratio analysis is used not only to assess element efficiency but also to ensure compliance with the weak beam-strong column design principle. This principle is important because it guarantees that the failure mechanism occurs in the beam, not the column, thus maintaining the overall stability of the building during an earthquake. Examination of the capacity ratio between beams and columns indicates that moment-frame configurations require larger column dimensions to meet this criterion due to the high lateral loads directly borne by the main elements. Meanwhile, in X-bracing and inverted-V-bracing structures, the design of the beam and column components has been adjusted based on the axial capacity of the bracing elements. With the presence of diagonal elements, a significant portion of the lateral force is transferred to the bracing, thereby reducing the load on the columns and main beams. This allows for the use of lighter and more efficient steel profiles, resulting in a lower D/C ratio overall. The D/C ratio overall structure provided in Figure 6, Figure 7, and Figure 8.

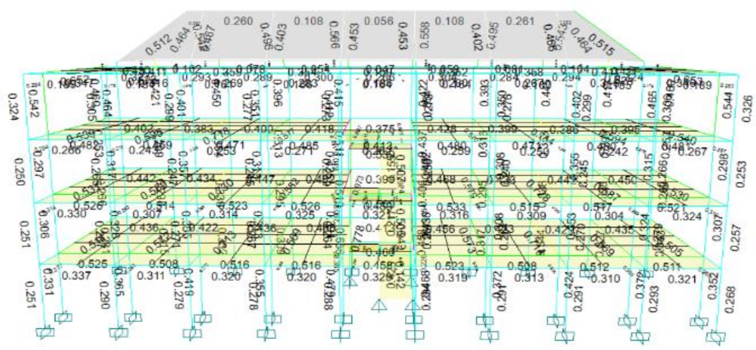


Figure 6. D/C ratio of moment-frame structure’s elements

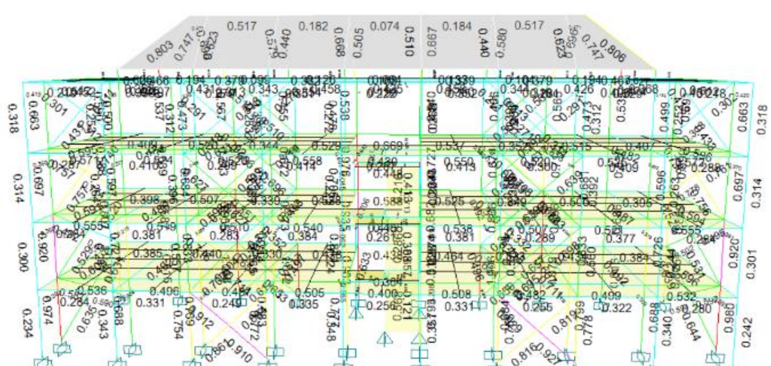


Figure 7. D/C ratio of X-brace structure’s elements

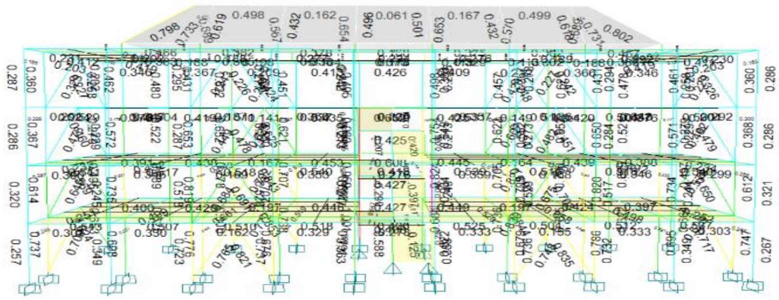


Figure 8. D/C ratio of inverted V-brace structure's elements

Based on the analysis results shown in Figure 6, Figure 7 and Figure 8, the D/C values for all structural elements in the three systems range from 0.209 to 0.980, indicating that all elements remain within the safe limits (D/C < 1.0) in accordance with the steel design requirements in SNI 1729:2020 (BSN, 2020b). This range indicates that no elements are overstressed, and the structural design meets the strength and stability requirements required for educational buildings in high-seismic zones.

3.4 Material Cost Estimation

Table 1 provides a summary of the main structural elements (beams, columns, and bracing) used in each system: moment frame, X-bracing, and inverted-V bracing. This summary includes the type and number of structural components as well as the total steel material requirements for each configuration.

Table 2. Material weight of the structures

Structural Elements	**Steel Profile**	**Material Weight**		
		Moment Frame (kg)	**X-Bracing (kg)**	**Inverted-V Bracing (kg)**
Beam	IWF200x100	16160.41	16160.41	16160,41
	IWF250x125	1069.92	18175.66	18192,01
	IWF300x150	21188.08	442.93	442,92
	IWF350x175	1533.37	3858.31	3858,31
	IWF400x200	15889.51	13080.36	13080,36
Column	H400	24765.09		
	H350	9845.45		
	H300	13591.93	135.95	3737,78
	H250	2615.18	19875.37	18044,74
	H200	1802.14	7208.56	7208,56
Bracing	H250		6661.97	
	H200		4590.82	4310,28
	H150		4086.89	4170,09
Total		108461,08	94287.63	89189.12

ISSN: 2456-3676

The calculation results indicate that the steel material requirements are significantly influenced by the structural system configuration used. The Open Frame System requires a total of 108,461.08 kg (≈108 tons) of material, making it the system with the highest steel consumption. This reflects that without bracing elements, the structure must rely on larger dimensions and numbers of main elements to achieve adequate stiffness and stability against lateral loads. In contrast, the Bracing-X system demonstrates better efficiency with a material requirement of 94,287.63 kg (≈94.3 tons). The contribution of diagonal elements in this system significantly reduces the loads that must be borne by the main beams and columns, allowing the use of lighter and fewer steel profiles. The Bracing-X system demonstrates efficiency by reducing steel volume by approximately 13% when compared to the Open Frame System. The Inverted-V Bracing System recorded the lowest material requirement, at 89,189.12 kg (≈89.2 tons). Despite having a different diagonal configuration than the Bracing-X, this system is still able to provide equivalent lateral stiffness, but with a force distribution that allows for further reduction in steel volume. The reduction in material requirements compared to open framing is nearly 18%, making it the most cost-effective alternative in terms of steel volume. Assuming a profile steel price of Rp 18,000/kg, including fabrication and assembly. The estimated material costs for each system are as shown in Table 3.

Table 3. Cost comparison

Structure Model	**Quantity (kg)**	**Total Amount (Rp)**	**Comparison (%)**
Moment Frame	108461.08	1.952.299.440	0
X-Bracing	94287.63	1.697.177.340	-13.1
Inverted-V Bracing	89189.12	1.605.404.160	-17.8

The estimated steel material costs for each structural system show significant differences. The Open Frame System has the highest total cost, which is Rp 1,952,299,440, due to the need for larger main elements to achieve structural rigidity without the aid of bracing. The Bracing-X System requires a cost of Rp 1,697,177,340, while the Inverted-V Bracing System records the lowest cost, which is Rp 1,605,404,160. If the Open Frame system is used as a 100% reference, the Bracing-X system provides a cost savings of 13.1%, and the Inverted-V Bracing system provides an even greater savings of 17.8%. This comparison shows that the use of bracing systems improves structural performance and provides significant economic efficiency in the use of steel materials. This comparison shows that the Inverted-V Bracing system is the most economical choice in terms of steel material usage, followed by Bracing-X. These two systems are not only more cost-efficient but also meet the structural stiffness requirements for educational buildings in high-seismic zones. These findings reinforce the importance of selecting the right structural system when designing multi-story steel buildings, especially for vital functions like schools.

From an architectural perspective, the use of bracing systems such as X-bracing and inverted-V bracing does present its own challenges in terms of spatial flexibility and interior aesthetics. The diagonal elements characteristic of bracing systems can disrupt spatial layouts, especially in areas that require openness, such as classrooms, corridors, or public areas. However, with careful architectural planning, this challenge can be overcome by placing bracing in non-critical areas or by integrating designs that align structural elements with architectural elements. In fact, in some cases, bracing can be used as an expressive element that strengthens the character of a building's design, especially in industrial or modern architectural approaches.

4. Conclusion

This study shows that the choice of a steel structural system has a significant impact on the material efficiency and construction costs of a four-story building in a high-seismic zone. The moment-frame system, while providing spatial flexibility, requires the highest steel quantity and material costs due to the absence of lateral bracing elements. In contrast, the X-bracing and inverted-V-bracing systems effectively increase structural stiffness, thereby reducing loads on the main elements and resulting in better material efficiency. In terms of structural performance, all three systems demonstrated maximum drift and interstory drift within safe limits, according to SNI 1726:2019. The Demand-to-Capacity (D/C) ratio for all elements was also below 1.0, indicating that the design met strength and stability requirements. The bracing system also allows for a more consistent application of the weak-beam-strong-column principle. Economically, the inverted-V-bracing system provides up to 17.8% savings in steel material costs compared to the open-frame system, while the X-bracing system provides savings of 13.1%. By considering aspects of stiffness, safety, and cost efficiency, the inverted-V bracing system can be recommended as an optimal structural alternative for educational buildings in high earthquake zones, such as Bali Province.

The results of this study provide a significant contribution in comparing the technical and economic efficiency of three steel structural systems in a four-story building located in a high-seismic zone. However, this research has several limitations. First, the study is limited to four-story buildings and is still relative to structures with fewer or more stories. Second, this study focused only on areas with high seismicity, such as Bali Province, which limits the generalizability of the findings to areas with moderate or low seismic risk that may require different design approaches. Third, non-structural aspects, such as spatial flexibility, architectural aesthetics, and user comfort, have not been analyzed in depth, despite the potential impact of bracing systems on interior design and spatial function.

Further research is strongly recommended in several areas of development. First, comparative studies should be conducted on similar structural systems in buildings of varying heights, including low-rise and medium-high-rise buildings, to gain a more comprehensive understanding of bracing system efficiency across building scales. Second, the analysis should be extended to moderate- and low-seismic zones to assess whether the technical and economic efficiency of bracing systems remains consistent under lighter seismic loads. Third, the integration of structural analysis with architectural design needs further development. Fourth, the use of a sustainability approach that includes calculating the life-cycle cost of each structural system will help parties make decisions based on long-term efficiency.

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Acknowledgments

This research received no specific financial support from any funding agency.

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