Comparative analysis of structural performance and cost efficiency of reinforced concrete and steel for a three-story warehouse in high-risk seismic zones

Ilian DJEBBARI[1,a], Fahmy HERMAWAN[2,b], Usman WIJAYA[2,c], Easther Sistha Parameswari WIBISONO[2,d]

[1]Polytech Nantes, Rue Christian Pauc, 44300 Nantes, France

[2]Universitas Trisakti, Kampus A, Jl. Kyai No.1, Grogol, Jakarta Barat 11440, Indonesia

[a]ilian.g.djebbari@gmail.com, [b]fahmy.hermawan@trisakti.ac.id, [c]usman.wijaya@trisakti.ac.id, [d]easthersistha@gmail.com

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Abstract. This study compares the structural performance and cost efficiency of reinforced concrete and steel for a three-story warehouse in Tangerang, Indonesia, a high seismic risk zone. Using ETABS, the structures were modeled and analyzed according to SNI and AISC standards. The concrete structure exhibited higher base shear forces due to its greater weight, increasing seismic demands, while the steel structure, though demonstrating higher displacements, remained within allowable limits due to its ductility. The maximum displacements in the steel structure were 0.148 m in the X direction and 0.084 m in the Y direction, compared to 0.048 m and 0.047 m for the concrete structure. A detailed cost comparison showed that while the initial material costs for the steel structure were higher, the reduced weight decreased the required foundation size, potentially lowering overall construction costs. This makes steel a competitive alternative for regions with high seismic activity, where flexibility and energy dissipation are critical. The study concludes that for high-risk seismic zones, the steel structure offers better performance, though the concrete structure remains more cost-efficient in areas with moderate seismic risks.

Introduction

Structural design in high-risk seismic zones like Tangerang, Indonesia, requires careful consideration of material properties and construction methods to ensure safety and cost efficiency. The seismic force increase continuously for low to high-rise buildings in Jakarta (20 km away from Tangerang) due to change including the study of seismicity, site location, soil type classification, determination of structural periods, seismic response factor, structural system, and the corresponding design with detailing requirements, also showed that the most significant increase of seismic force which was approximately 40% was recorded in 2002 and this was the primary cause of seismic retrofitting [3]. Reinforced concrete and steel are two widely used materials, each offering unique advantages—concrete for its compressive strength and cost-effectiveness, and steel for its ductility and construction speed.

This study focuses on the design of a three-story warehouse in Tangerang, comparing the performance of reinforced concrete and steel in resisting seismic forces. The analysis will assess displacement, story drift, and associated construction costs.

This research aims to guide engineers and developers in selecting the optimal construction material for similar projects in seismic zones.

The study is limited to the structural design and analysis of the warehouse, considering only structural costs and excluding long-term maintenance. Performance metrics will focus on displacement, story drift under seismic loads and torsion.

The paper is organized as follows: The next section reviews relevant literature and standards. The methodology section details the design and analysis process, including the use of ETABS for structural modeling. The results and discussion section presents findings on displacement, story drift, and cost comparison. Finally, the paper concludes with recommendations and suggestions for future work.

Literature Review

Designing structures in seismic zones requires understanding the standard codes, the regulations and how materials respond to dynamic forces. Reinforced concrete and steel are often chosen for their respective strengths—concrete for compressive strength and steel for ductility. SNI 1726:2019 [5] outlines the requirements for seismic design in Indonesia, emphasizing strength, stiffness, and ductility.

Both materials must comply with these standards to ensure adequate performance during an earthquake, focusing on limiting displacements, preventing excessive story drift and limiting torsion.

Studies comparing the seismic performance of reinforced concrete and steel show that steel structures often perform better due to their energy absorption and ductility. Although steel has higher initial costs, it typically results in lower displacement and story drift, making it preferable in high-risk seismic zones. Conversely, reinforced concrete is favored in budget-constrained regions where it can still meet seismic requirements.

In Indonesia, the design of reinforced concrete and steel structures follows SNI standards. SNI 2847:2019 provides guidelines for concrete structures, while SNI 1729:2020 covers steel design. Both standards emphasize seismic load considerations, with ETABS software supporting the modeling and analysis of these loads for optimized design [6,7].

It is found that the fixed base version of steel concrete has less seismic responses as compared to the Fixed Base RCC building [1].

The fundamental period constraints play a crucial role in optimizing the design of composite buildings and determining the required structural materials. Ignoring these constraints can lead to cost-effective designs but result in unacceptable vibration performance. Conversely, adhering to these constraints increases material costs significantly. Proper consideration of the fundamental period is essential during design; using an incorrect Seismic Design Category (KDS) can lead to oversized structural elements and higher costs. [2]

Methodology

The case study focuses on the structural design of a three-story warehouse in Tangerang, a region with high seismic risk. The building's total height is 13.445 meters, with distinct floor levels: Ground Floor: 680.4 m² (16.2 m x 42 m) for heavy storage or industrial use, First Floor: 592.65 m², including a 9.45 m² smaller slab, Second Floor: 498.6 m², including a 12.6 m² smaller slab.

The architectural plans recommended a mixed-use structure employing both reinforced concrete and steel to balance strength, flexibility, and cost. This study evaluates two alternative designs: one in reinforced concrete and the other in steel, comparing their performance in terms of displacement, story drift, and construction costs.

Reinforced concrete beams and columns were presized according to SNI 2847-2019, Chapter 18, while respecting the architect's suggestions. Beams should have a minimum span-to-depth ratio of: Clear span (λn) $\geq 4d$, minimum beam width: $bw = \min(0.3h, 250\text{ mm})$ and beam projection beyond column width: $\max(c2, 0.75c1)$. While columns should respect a minimum cross-sectional dimension of 300 mm and an aspect ratio bigger than 0,4 [6].

Steel beams and columns were presized following SNI 1729-2020, considering the architect's recommendations. For beams we must respect the load determination: $w_u = 1.2w_D + 1.6w_L$, the trial section selection: depth = 1/10 to 1/12 of span length and beam size: $S_{req} \geq M_u / (0.9 * F_y)$, verified for deflection ($\Delta_{max} = L/360$) and shear ($V_u = w_u * L / 2$). For columns we must respect axial load calculation: combined dead and live loads, effective length factor (K): based on column end conditions, trial section selection: slenderness ratio $KL/r < 200$ and buckling check: compare axial load to critical buckling load [7].

For the structural Modeling in ETABS, we input several factors: the geometry as modeled to reflect the 13.445-meter height and varying floor areas, the material properties as concrete fc′=30 MPa, Steel Fy=240 MPa, Rebar Fy=420 MPa, gravity loads as dead and live loads per SNI standards, including 5.884 kN/m^2 for slabs and 0.58 kN/m^2 for the roof, seismic loads as applied per SNI 1726-2019, using a response spectrum, the reinforced concrete model include fixed supports assumed at column bases and the steel model include fixed supports also assumed for column bases. The reinforced concrete model includes columns: 400x600 mm^2 (sides), 600x350 mm^2 (interior), T-Beams: BT 250x700 mm (primary), BT 250x600 mm (secondary) and slabs of 15 cm reinforced concrete.The steel model has columns : HB350, WF588, beams: WF500/WF450 (primary), WF350 (secondary) and slab of 15 cm composite slab [5].

In the structural analysis of the warehouse, accurately accounting for seismic forces is crucial. The lateral loads for each floor were calculated manually in two directions, X and Y, using the weight values provided by ETABS and the relevant formulas from SNI 1726:2019 [5]. The weight of each floor, as calculated by ETABS, served as the basis for determining the seismic mass, which is essential for calculating the forces the building must resist during an earthquake. For the reinforced concrete model, ETABS provided periods of Tx=0.431s and Ty=0.428s. For the steel model, ETABS initially provided Tx=0.808 and Ty=0.75s, but these exceeded the maximum allowable period according to SNI 1726:2019, which is Tmax=0.409s, derived from Cu (Table 17), Ct, and x (Table 18). Therefore, the value of Tmax=0.409s was used for the steel model in both directions. The seismic coefficient (Cs = 0.084875) was determined based on specific seismic parameters of the site, including the building's importance factor, site class, and occupancy category, as specified in SNI 1726:2019. The lateral load (V) for each floor was calculated in both the X and Y directions using the formula, where W represents the seismic weight of the floor, and Cs is the seismic coefficient:

$$V = C_s \times W \tag{1}$$

After determining the lateral loads, they were inserted into the ETABS model. This step was crucial for accurately simulating the building's response to seismic forces, allowing the structural analysis to reflect real-world conditions as defined by SNI 1726:2019 [5].

Table 1 : Lateral load values for reinforced concrete model

Story	wi [kN]	hi [m]	Cvx	Fx [kN]	Vx [kN]	Cvy	Fy [kN]	Vy [kN]
Low part of the roof	726,1	10,887	0,13	160,59	160,59	0,12	148,82	148,82
Warehouse 2nd floor	6721,0	5,5	0,63	768,90	929,49	0,56	713,27	862,09
Warehouse 1st floor	7548,5	2,75	0,37	442,23	1441,51	0,32	410,66	1272,75
Total	14995,65			1441,51			1272,75	

Table 2 : Lateral load values for steel model

Story	wi [kN]	hi [m]	Cvx	Fx [kN]	Vx [kN]	Cvy	Fy [kN]	Vy [kN]
Low part of the roof	216,8	10,887	0,06	45,02	45,02	0,07	50,64	50,64
Warehouse 2nd floor	4035,4	5,5	0,61	436,75	481,77	0,63	447,21	497,85
Warehouse 1st floor	4164,1	2,75	0,33	232,56	714,33	0,30	216,48	714,33
Total	8416,3			714,33			714,33	

In the steel model, the lateral loads are generally lower compared to the reinforced concrete model, reflecting the material's higher flexibility and energy dissipation capacity. The load distribution shows a more gradual increase from the first to the second floor, with a significant decrease at the roof level, indicating that the steel structure handles seismic forces differently, likely due to its lower mass and higher ductility. The comparison between the two models indicates that while the reinforced concrete structure bears higher lateral loads, the steel structure exhibits a more even distribution of forces across the floors. This is consistent with the expected behavior of the two materials under seismic loading, where reinforced concrete, due to its higher mass, attracts more seismic forces, while steel, with its higher ductility, experiences lower but more evenly distributed forces. These findings are crucial in determining the most suitable material for seismic resilience and cost efficiency.

To find the total cost of the construction, several steps need to be followed. The first step is to define the cost of the preparation work. The second step is to define the cost of the construction itself. The preparation includes several elements that are necessary to consider while doing the cost estimation, so that it can reflect well on the final price of the structure construction. It includes: mobilizations and demobilization, measuring and bouwplank work, electricity, shop drawing, site management, workers insurance, and cleaning. Each work item has its own volume that is multiplied by its unit price. The unit price used in the calculation uses the DKI Jakarta unit price analysis calculation which already includes labor, materials, and 10-15% overhead and profit based on SNI. The multiplication of volume and unit price result is summarized to get the total price. The steel structure work is divided into several work items which includes steel column, steel frame, and baseplate. Each steel type needed in the work has its volume in kilograms which needs to be multiplied by its unit price to get the total price.

Table 3 : Cost analysis final values for both models

	Preparation work	Structure construction	Total
Steel Building	IDR 407.500.000,00	IDR 2.914.510.968,87	IDR 3.322.010.968,87
Concrete building	IDR 210.000.000,00	IDR 2.018.223.390,00	IDR 2.228.223.390,00

The cost analysis shows a significant price difference between the two models. The total cost for the steel structure is IDR 3,322,010,968.87, while the reinforced concrete structure costs IDR 2,228,223,390. This represents a 48.6% higher cost for the steel structure. The higher cost of steel is due to more expensive materials and installation complexity. However, despite the higher cost, steel may provide better performance in seismic zones, making it a valuable option depending on the project’s priorities.

Results and discussion

The seismic performance of the warehouse was assessed by analyzing three key factors: deformation, drift, and torsional amplification for both the reinforced concrete and steel models.

These factors were compared to the allowable limits in both the X and Y directions to ensure compliance with seismic code requirements. The analysis provides a comprehensive understanding of how each material behaves under seismic loads and the capacity of the structure to remain within safety limits.

Figures 1 and 2 show the deformation results for both models. In the reinforced concrete model (Figure 1), the maximum deformation recorded at the low part roof is 0.048 m in the X direction and 0.047 m in the Y direction. These values are well below the allowable limit of 0.167 m, demonstrating that reinforced concrete, with its rigid nature, effectively resists seismic forces without excessive deformation. For the steel model (Figure 2), the deformations are higher, with a maximum value of 0.148 m in X and 0.084 m in Y. These values also remain below the permissible limit of 0.218 m, indicating that despite experiencing higher deformation than reinforced concrete, the steel structure remains within safe limits. This increased flexibility in the steel model can be advantageous in high seismic risk areas, as it allows the structure to absorb and dissipate seismic energy without compromising overall stability.

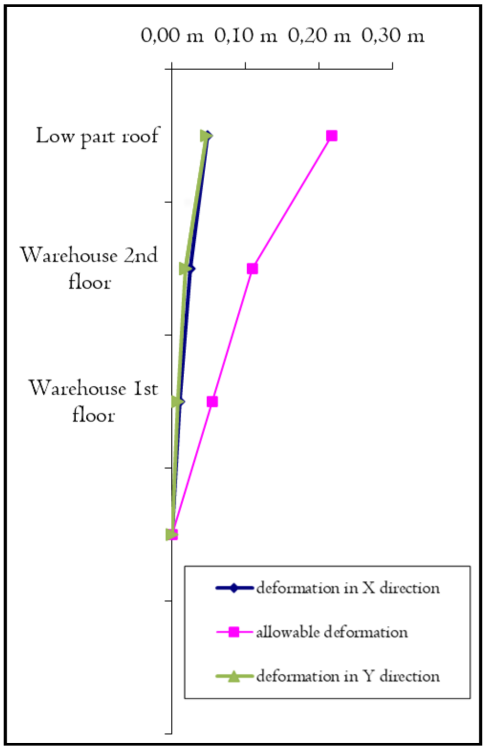

Figure 1 : Deformation in X and Y direction (Concrete model)

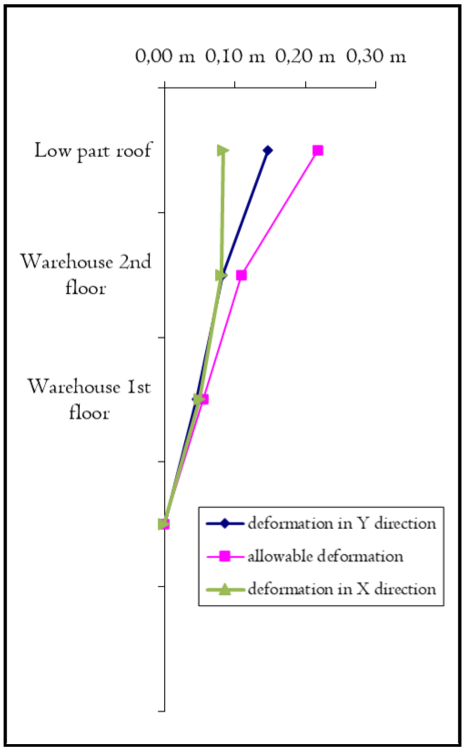

Figure 2 : Deformation in X and Y direction (Steel model)

The deformation results highlight the differences between the materials. The reinforced concrete model shows minimal deformations, well below the allowable limits, reflecting its rigidity and resistance to movement under seismic loads. In contrast, the steel model exhibits higher deformations due to its ductility, allowing for better energy absorption while still remaining within safety limits. Both materials meet the seismic code requirements, with concrete prioritizing stiffness and steel optimizing flexibility and energy dissipation.

Drift, which represents the relative displacement between floors, was also analyzed for both models, with the results presented in Figures 3 and 4. The allowable drift limit was plotted alongside the drift values to ensure that the design remains within permissible limits. For the reinforced concrete model (Figure 3), the maximum drift occurs at the roof level, with values of 0.023 m in the X direction and 0.029 m in the Y direction. These values are well below the allowable limit of 0.083 m, indicating the structure's capacity to withstand seismic forces with minimal drift. In the steel model (Figure 4), the drift values are higher, with maximum drifts of 0.065 m in the X direction and 0.084 m in the Y direction at the roof level. However, these drifts remain within the allowable limit of 0.108 m. The greater drift in the steel model is consistent with the material's higher ductility, which allows it to absorb seismic energy effectively without compromising structural integrity.

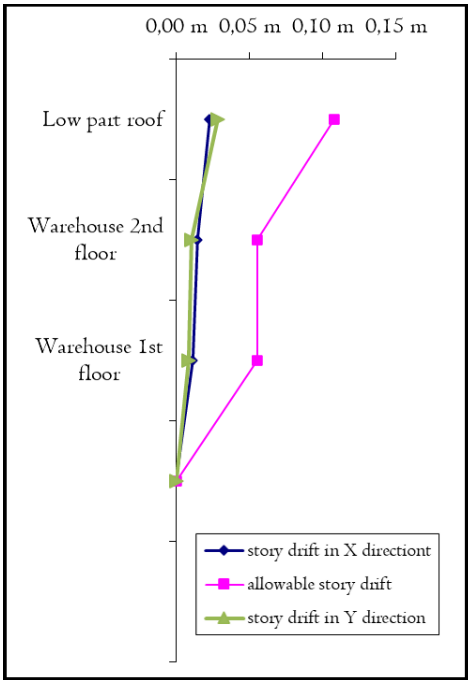

Figure 3 : Drift in X and Y direction (Concrete model)

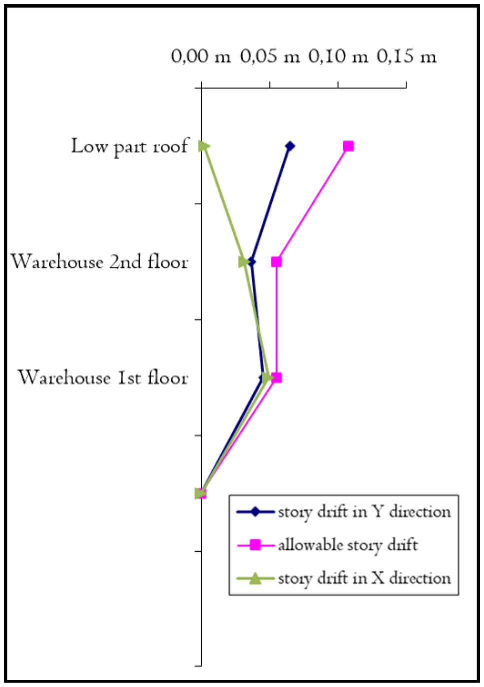

Figure 4 : Drift in X and Y direction (Steel model)

The higher drift observed in the steel structure is consistent with its material properties, which allow for greater flexibility and movement under seismic forces. This flexibility, while resulting in higher drift values, remains within safe limits, demonstrating the steel structure's ability to absorb seismic energy without compromising its stability. Torsion is a critical factor in seismic design, as it can lead to uneven force distribution, potentially destabilizing a structure if not properly managed. The Figures 5 and 6 illustrate the torsion amplification for both the reinforced concrete and steel models in the X and Y directions.

For the reinforced concrete model (Figure 5), the torsion amplification values are relatively low in both directions, with Ax and Ay consistently below 1. These values indicate that the concrete structure resists torsional effects effectively, maintaining its stability even under seismic loads. The maximum amplification occurs at the roof level, with values of 0.009 m in both X and Y directions, which is well within acceptable limits. Lower floors exhibit even smaller amplification values, further confirming the concrete model's stiffness and resistance to torsion. In contrast, the steel model (Figure 6) shows higher torsion amplification values, particularly in the X direction. At the roof level, the torsion amplification in X reaches 0.035 m, while in the Y direction, it reaches 0.019 m. Although these values are higher than those observed in the concrete model, Ax and Ay remain below 1, indicating that torsion does not pose a significant risk to the stability of the steel structure. The higher values in the steel model are consistent with its increased flexibility and ductility, allowing it to accommodate more significant deformations without compromising structural integrity.

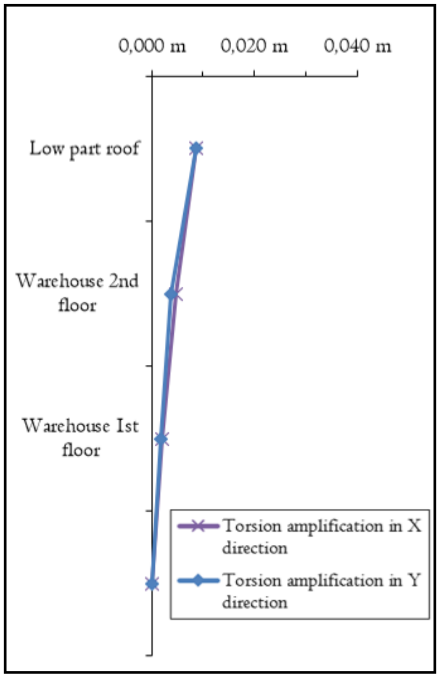

Figure 5 : Torsion amplification in X and Y direction (Concrete model)

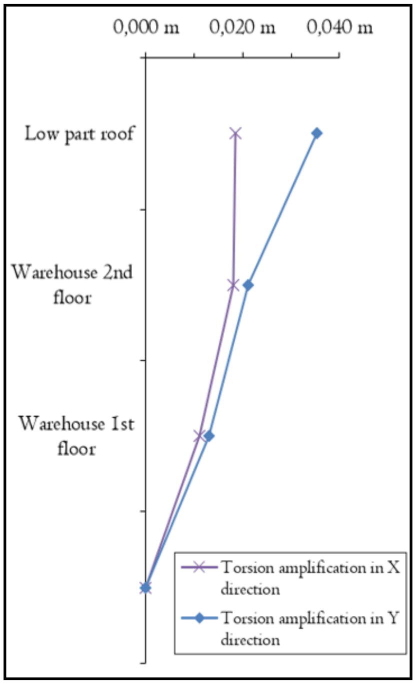

Figure 6 : Torsion amplification in X and Y direction (Steel model)

The torsion amplification values for both models suggest that the reinforced concrete structure exhibits less susceptibility to torsion compared to the steel structure, which is expected due to concrete's higher stiffness. The lower amplification in the concrete model confirms its ability to maintain stability with minimal torsional influence during seismic events. In the steel model, although the torsion amplification values are higher, they remain well within the safe limits. This demonstrates that while steel is more flexible and may experience greater torsional effects, it can effectively manage and dissipate seismic energy without posing a structural risk. Finally, the ratio between the average drift of two points (Davg) and the maximum drift remains below 1.2 for both models, confirming that no significant torsional effects are present. As a result, there will not be a structurally significant reduction in either flexural or shear strength, further ensuring the safety of both structures under seismic loading.

Conclusion

The performance of both buildings shows deformations that comply with the standard seismic code requirements. For the reinforced concrete building, the maximum deformation at the roof level is 0.048 m in the Y direction, while for the steel building, it reaches 0.148 m in the Y direction. Similarly, the drift values show a 0.029 m drift for the concrete building in the Y direction, compared to 0.065 m for the steel building in the same direction. These results highlight that the steel structure is significantly more ductile than the reinforced concrete structure, especially in the Y direction, which is consistent with the inherent material properties of steel allowing for greater flexibility and energy absorption under seismic loads. In terms of building weight, the reinforced concrete structure is considerably heavier, with a total weight of 14,995.6 kN, compared to the 8,416.3 kN for the steel structure. This difference in weight has a direct impact on the base shear forces, where the reinforced concrete building experiences a base shear of 1,441.51 kN in the X direction, while the steel building has a significantly lower base shear of 714.33 kN in the X direction. These findings confirm that lighter buildings are subject to smaller base shear forces, which can lead to reduced seismic demands on the structure.

Despite these differences, both structures perform within the allowable limits for deformation, drift, and base shear, indicating that both materials can be effectively used in seismic regions depending on project priorities. While the reinforced concrete building is more rigid and exhibits less deformation and drift, it comes at the cost of increased weight and consequently higher seismic forces. The steel structure, on the other hand, demonstrates superior ductility and energy dissipation, which are crucial for maintaining structural integrity during intense seismic events. However, this performance is accompanied by higher construction costs, largely due to the cost of steel and the specialized labor required for its construction.

Both building models could be optimized further to reduce construction costs while staying within the safety margins dictated by the seismic codes. For the reinforced concrete structure, reducing the overall stiffness slightly could bring the deformations and drift closer to the allowable limits, which would decrease the amount of material used and, in turn, lower both material and labor costs. This would result in a more cost-effective structure while still ensuring safety and stability under seismic conditions. For the steel structure, a similar approach could be taken by adjusting the design to reduce the excess flexibility, which would allow the building to stay within the acceptable deformation range but with less material use. This optimization would help bring down the cost of the steel structure, making it a more attractive option for seismic zones without compromising its ability to absorb and dissipate energy effectively. By implementing these design optimizations, both structures could achieve a more balanced cost-to-performance ratio, aligning more closely with the allowable limits and offering the potential for cost savings while maintaining the necessary seismic resilience.

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