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Analysis of a 40-Story Office Building Combining a Post Tensioned Flat Slab with Separated Gravity Lateral Resisting Implementation †

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Abstract: Compared to other countries, the adoption of post-tensioned flat slab (PTFS) in Indonesia is relatively limited due to the susceptibility of flat slab to lateral forces. Nevertheless, flat slabs in high seismic zones scan still be achieved by utilizing the separated gravity lateral resisting (SGLR) system. This study analyzes a 40-story office building by comparing the structural response, volume, and cost of PTFS with conventional structures. The findings reveal that PTFSs exhibit greater story drift and displacement but experience reduced story shear and overturning moments with a reduction in concrete volume of up to 10% and a 6% decrease in overall costs.

Keywords: post-tensioned; flat slab; SGLR system; dual system; volume analysis; cost analysis

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1. Introduction

Over the past decade, the construction of tall buildings has surged, driving civil engineers to invent more effective design solutions. A critical challenge in designing these structures involves developing a robust lateral stability system, an efficient gravity system, and a reliable foundation design. The moment resisting frame (MRF) system, also known as a rigid frame, addresses these needs by rigidly connecting beams and columns to provide lateral resistance. The MRF system is commonly employed for both gravity and lateral stability purposes [1]. According to ACI 318-19 [2] and SNI 1726:2019 [3], MRFs must adhere to specific criteria, based on seismic design categories. In regions classified under seismic design categories D, E, or F, MRFs must meet the detailing requirements for special moment frames. These requirements ensure that the MRF can safely undergo the extensive inelastic deformations anticipated in high seismic zones, promoting a ductile inelastic response. The primary objectives when designing special moment frames are to achieve a strong-column–weak-beam design that distributes inelastic responses across multiple stories, to prevent shear failure, and to incorporate details that facilitate ductile flexural response in yielding regions. These design principles are crucial for ensuring the structural integrity and resilience of tall buildings in seismic-prone areas [4,5].

Lateral forces acting on structures, such as earthquakes and wind loads, can be critical, especially in tall buildings. A shear wall is one of the common lateral resisting systems that have been provided to act as cantilever beams, fixed at their base to carry loads down to the foundation. Shear walls may be added as concrete walls, enclosing stairways or elevator shafts [6]. Special moment frames have also found use in dual systems that combined special moment frames with shear walls. The addition of shear walls can improve the performance of flat-slab systems in resisting lateral loads [7]. In the design based on ASCE 7-16 [8], the moment frame is required to be capable of resisting 25% of the designed seismic forces, while the total seismic resistance is provided by the combination of the moment frames and the shear walls [4].

In addition to the structural resistance system, the construction material also plays an important role. One critical determinant of a structure's overall material is the chosen slab construction method. The flat-slab method is prevalent due to its simplicity, eliminating the need for complex formwork and thus accelerating construction and reducing costs. The reduction in the volume of concrete for the flat slab structure, compared to a conventional slab, may reach 5% to 14% of the total volume of concrete [9]. This also offers the benefit of reducing cement consumption in the construction industry, considering cementitious material contributes approximately 8% of global CO_2 emissions [10] as well as a reduction in the cost of construction. The cost of a flat-slab structure can be reduced by 15%, compared to conventional slab structures [11].

In flat-slab systems, punching failure is the most prevalent failure mode, resulting from the combined effects of shear and flexural stresses around the column. The punching shear strength is influenced by factors such as the dimensions, concrete type, thickness, flexural reinforcement, and other design considerations. One effective solution to enhance punching shear strength is the incorporation of a drop panel around the column. Flat slabs with drop panels (DPs), that are cast with the slab, will form a thicker concrete zone around the column. This addition will enhance the shear resistance of the impacted slab around the column, where the highest shear stresses occur, as well as reduce the overall slab thickness, while maintaining structural integrity [9,12,13].

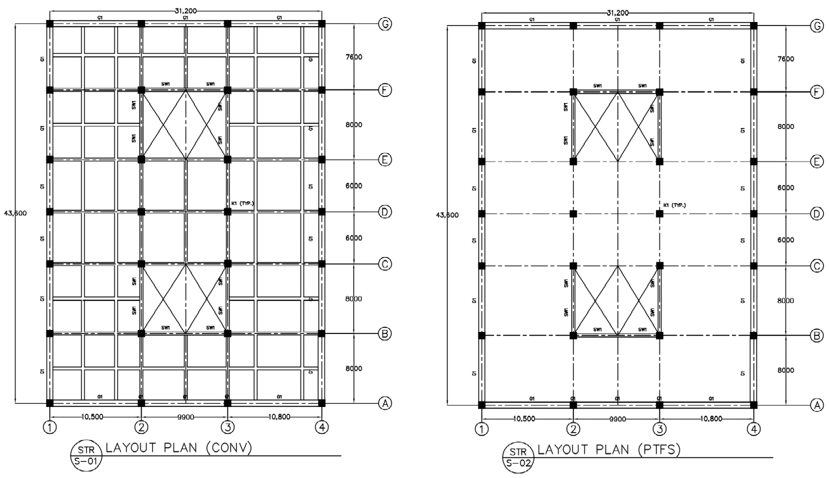
However, the strength and stiffness capacity of the flat-slab system are lower, compared to the frame system. Flat slab is considerably more flexible for horizontal loads than the conventional frame system [14]. Therefore, the flat-slab structure can be designed as a post-tensioned flat slab (PTFS) to conserve concrete materials, reduce the overall load of the structure, enhance the space, and reduce the material volume and cost [15]. PTFS may be a solution to improve the seismic performance of flat-slab systems [16]. It allows us to thin the slab and lessen the dead load to its own weight, as well as reduce the volume by 20%, and reduce the cost of materials, compared to the conventional slab system [17–19]. PTFSs have gained widespread acceptance in countries such as the United States, Australia, South Africa, Thailand, India, and Korea [20,21]. By mid-2006, over 50% of housing in the United States incorporated PT slabs. By the end of 2012, it was estimated that more than 0.2 billion square meters of building area in the United States had utilized PT slabs [22]. In contrast, the use of PT flat slabs in Indonesia remains limited and is primarily confined to basements. This hesitancy is likely due to the susceptibility of flat-slab structures to lateral loads, particularly in high seismic zones, such as Indonesia. Flat slabs are prone to failure around columns from punching shear, significant deflections, and lack the rigidity at the slab-column joint that a beam-column connection provides [23].

Given that flat slabs are susceptible to the lateral load, it is essential to incorporate additional elements that function as a lateral load-resisting system. The implementation of the SGLR system may provide a viable solution, particularly for utilizing flat slabs in high seismic zones. The SGLR system is achieved by distinctly separating the elements that function as lateral load-resisting systems from those that serve as gravity load-resisting systems. Consequently, certain elements may function solely as gravity-only systems. In this analysis, the post-tensioned flat slab serves exclusively as a gravity-load resisting system and shear walls, combined with special- moment resisting frames acting as lateral resisting systems. Shear walls in flat slabs shows a good performance in terms of lateral resisting systems [24]. In previous studies, the SGLR system has been investigated primarily in steel structures [25,26]. Compared to the rigid frame system, the SGLR system tends to have smaller vibration periods, has better lateral deformation control capacity, and reduces the inter-story drift ratios [25]. The damage components, based on a fragility analysis, show that the limit value of the story drift for high-rise composite structural systems with SGLR system is 1/800 to 1/1000 [26].

Nevertheless, PTFSs can be effectively employed in such regions through the implementation of the separated gravity lateral resisting system (SGLR system), which separates the lateral resistance and the gravity load resistance. Therefore, this research aims to foster greater interest and utilization of PTFS in Indonesia.

2. Research Method

In this study, the analysis will be conducted based on a case study of a 40-story office building located in Depok, West Java, Indonesia. The floor plans of each story will be made typical as shown in Figure 1. In the PTFS structure, the use of beams will be reduced so that the beams are only used in the perimeter. The equivalent static method and response spectrum analysis will be used to analyze the behavior of the structures. The specifications of the materials used in the model are shown in Table 1, according to the materials in SNI 2052:2017 [27], and the loads used in the model are shown in Table 2, and have been adjusted to the SNI 1727:2020 [28], SNI 1726:2019 [3], and ASCE 7-16 [8].



(**a**) (**b**)

Figure 1. Floor plan: (**a**) Conventional structure and (**b**) PTFS structure.

Table 1. Material specification.

Material	Specification	Value
Concrete	Compressive strength after 28 days (f_c')	35 MPa
Steel	Yield strength (f_y)	420 MPa
Tendon	Ultimate strength (f_{pk})	1860 MPa
Strand	Type	0.6″

Table 2. Value of DL, SIDL, LL, RL, WL, and Eq used in the model.

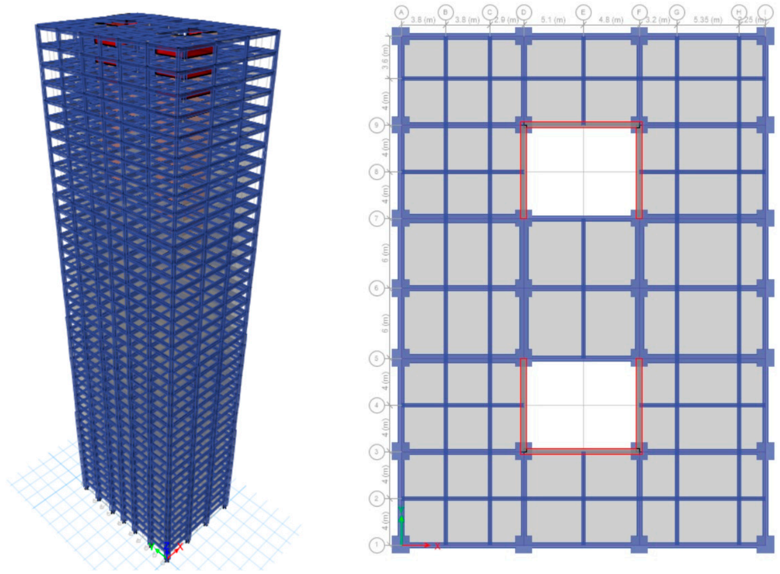
Type of Load	Specification		Value
Dead load	Concrete		24 kN/m^3
	Reinforcing steel		7850 kg/m^3
Super imposed dead load	Mechanical, electrical, plumbing		1.4 kN/m^3
Live load	Live load typical floor		2.4 kN/m^2
	Roof live		0.96 kN/m^2
Rain load	Rain load		0.6 kN/m^2
Wind load	Windward coefficient		0.8
	Leeward coefficient		0.5
	Wind speed		100 mph
	Gust and directionality factor		0.85
Earthquake load	Risk category		II
	Importance factor		1
	Site class		SE
	Spectral response acceleration parameter	S_s	0.9407
		S_1	0.437
	Design spectral acceleration parameter	S_{DS}	0.72
		S_{D1}	0.68
	Site coefficient	F_a	1.147
		F_v	2.236
	Response modification coefficient	R	7
	Overstrength factor	Ω_0	2.5
	Deflection amplification factor	C_d	5.5

The analysis will be conducted using the ETABS software, as shown in Figure 2. ETABS is a powerful tool that significantly enhances the engineers' capabilities in structural analysis and design. ETABS allows engineers to efficiently analyze, design, and detail structures, based on the defined structural elements and their assignments within the program [29]. In the PTFS structure, beam usage will be minimized. To enhance the punching shear capacity at the interior column, drop panels will be included in the design of PTFS structure. The interior columns in the PTFS structure will act as gravity only columns while the perimeter columns and beams will form the special moment resisting frames (SMRFs) and work alongside the shear walls as lateral resisting systems.

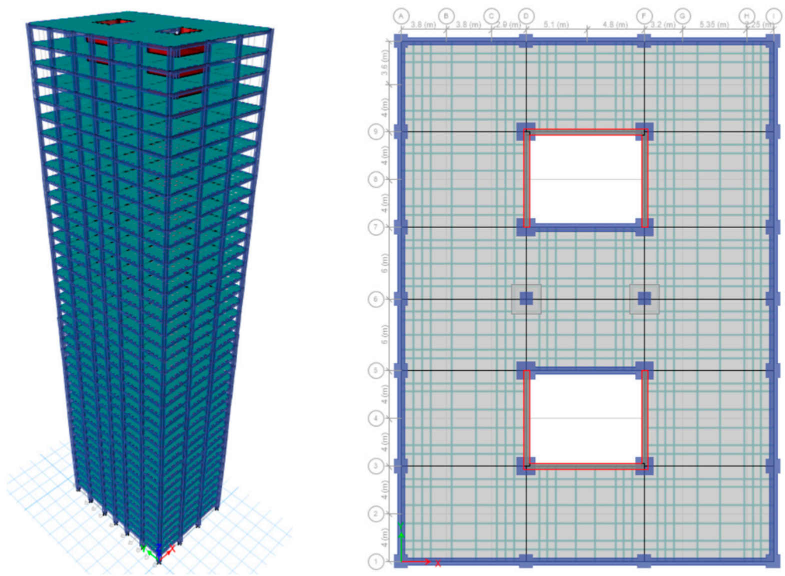
The analysis that will be carried out will compare the structure without the posts tensioned flat slab (PTFS) to the PTFS structure to determine:

1. the design of the columns, beams and slab, according to SNI 2847:2019 and SNI 1726:2019, for the conventional structure and the PTFS structure,
2. the structure response of the conventional structure and the PTFS structure,
3. the most efficient tendon layout for the PTFS structure
4. a comparative analysis of the material volume and a cost analysis of the conventional structure and the PTFS structure.

The most efficient tendon layout will be determined by comparing three variations based on the distribution of the tendon. The tendon will be distributed in the column strip and the middle strip. In variation 1, the distribution ratio is 70% in the column strip and 30% in the middle strip, in variation 2, it is 80% in the column strip and 20% in the middle strip, and in variation 3 it is 60% in the column strip and 40% in the middle strip. A comparative analysis will be conducted to evaluate the efficiency of both the conventional structure and the PTFS structure. The cost analysis will consider the material volume and the installation costs of bar reinforcement, concrete, tendons, and formwork.



(a)



(b)

Figure 2. ETABS model: (**a**) Conventional structure and (**b**) PTFS structure.

The design process will consider the iterative analysis to ensure compliance with the requirements. These include mass participation, period, scale factor for static equivalent and response spectrum analysis, dual system requirement (the moment frame is capable of resisting 25% of the designed seismic forces), cracked section factors for the shear wall, drift limits, P-Delta effects, and irregularities in both the conventional and the PTFS structure. Additionally, the design of the PTFS structure will also include an analysis for the allowable limit stress, displacement compatibility, and punching shear.

When designing the prestressed structure, it will be crucial to account for the losses in the strands to achieve a precise analysis. These losses can be categorized into immediate elastic losses and time-dependent losses. Immediate elastic losses occur during the tendon installation process, and include factors such as the elastic shortening of the concrete, anchorage losses, and frictional losses. Time-dependent losses, which manifest over time, are determined at the service-load limit state of stress. Time-dependent losses are caused by creep, shrinkage, temperature fluctuations, and steel relaxation [30]. In this analysis, losses will be calculated over a period of five years, with two different spans, as shown in Table 3. The longer span is parallel to the x-axis, while the shorter span is parallel to the y-axis. The remaining prestress in the tendons, after accounting for these losses, is 86% in the x-direction and 84% in the y-direction,

Table 3. Losses calculation.

Stage	Categories	X Direction		Y Direction	
		Stress (MPa)	**%**	**Stress (MPa)**	**%**
Initial	Initial stress, fpi (0.75 f_{pu})	1395	100%	1395	100%
	Anchorage-seating loss (A)	−114.653	−8%	−154.781	−11%
	Friction loss (F)	−88.591	−6%	−74.437	−5%
Adjusted initial stress, fpi (post tensioned)		1191.756	85%	1165.782	84%
Transfer (24 h)	Elastic shortening loss (ES)	0	0%	0	0%
	Steel relaxation loss (R)	−12.123	−1%	−12.123	−1%
Net stress at transfer stage (f_{pi} net)		1179.633	85%	1153.659	83%
Service (30 days)	Elastic shortening loss (ES)	0	0%	0	0%
	Creep loss (CR)	−6.658	0%	−1.406	0%
	Shrinkage loss (SH)	37.900	3%	37.900	3%
	Steel relaxation loss (R)	−5.989	0%	−5.270	0%
Effective stress (f_{pe})		1204.886	86%	1184.883	85%
At time t (5 years)	Steel relaxation loss	−8.110	−1%	−7.414	−1%
Net stress at time t		1196.776	86%	1177.469	84%

The design of the PTFS combines structural components with distinct roles: some resist only gravity loads, while others resist both gravity and lateral forces. This approach is essential to ensure that the flat slab, which is not designed to resist lateral loads, will be designed to resist gravity loads only. The separation of lateral load resistance from gravity load resistance can be effectively achieved through the implementation of the separated gravity lateral resisting (SGLR) system, which assigns lateral-force resistance to perimeter frames and shear walls, while the interior elements are designed to support only gravity loads. According to article 18.14 of SNI 2847:2019 [31], specific design requirements must be met for components intended to resist only gravity loads. Article 18.14.2 of SNI 2847:2019 requires that these components must be evaluated under the critical load combination of 1.2D + 1.0LL, without considering the design displacement, δ_u. These considerations are intended to enable the ductile flexural yielding of the structural system under the design displacement [31]. To ensure SGLR, moments will be released on gravity-only columns, allowing the perimeter frame and shear walls to bear most lateral forces. Subsequently, to ensure deformation compatibility, a joint drift, equal to the maximum earthquake-induced drift, will be applied. In the analysis, the maximum seismic-force-induced drift sis found to be 3.228 mm in the x-direction and 3.085 mm in the y-direction. Once the drift is applied, the gravity-only columns must be verified to withstand the combined load of 1.2D + 1.0LL and a joint drift with the axial, shear, and moment forces on the gravity column, as shown in Table 4. Gravity-only columns must be evaluated for axial and moment capacity, as well as shear capacity and confinement, to ensure they remain within the PMM capacity limits, and to verify that the columns can maintain adequate ductility when subjected to lateral drift forces.

Table 4. Internal forces on gravity only columns.

Direction	Condition	Axial-Flexural P (kN)	Axial-Flexural M2 (kN.m)	Axial-Flexural M1 (kN.m)	Value V1 (kN)	Value V2 (kN)
X	P abs max M2 abs max M3 abs max P abs max	851.2487 125.1245 219.8987 −848.869	172.0424 3942.6726 2242.2969 −149.7837	2.0004 4.5188 6.3988 6.6664	0.187 0.5324 1.3482 3.374	86.48 1602.2914 667.3224 −75.3078
Y	M2 abs max M3 abs max	−106.859 −106.2382	−275.1429 226.8361	3121.9495 3123.2685	1258.726 1259.369	−107.2534 87.8354

3. Result and Discussions

The variations in the maximum story drift, story displacement, story shear, and the overturning moment are presented graphically in Figure 3. These values are derived from the calculations performed in ETABS with an iterative analysis to ensure compliance with the requirements for conventional and PTFS structures. The structure-response results showed that story drift and displacement generally increase as the number of stories rises, while story shear and the overturning moment tend to decrease with an increase in the number of stories. In comparison, the maximum story drift and story displacement in PTFS structures are greater than in conventional structures; meanwhile the story shear and overturning moment of PTFS structures are lower than those of conventional structures. These results align with previous studies that show that flat-slab structures have a higher story drift, higher story displacement, and lower story shear, compared to conventional structures [12,32,33].

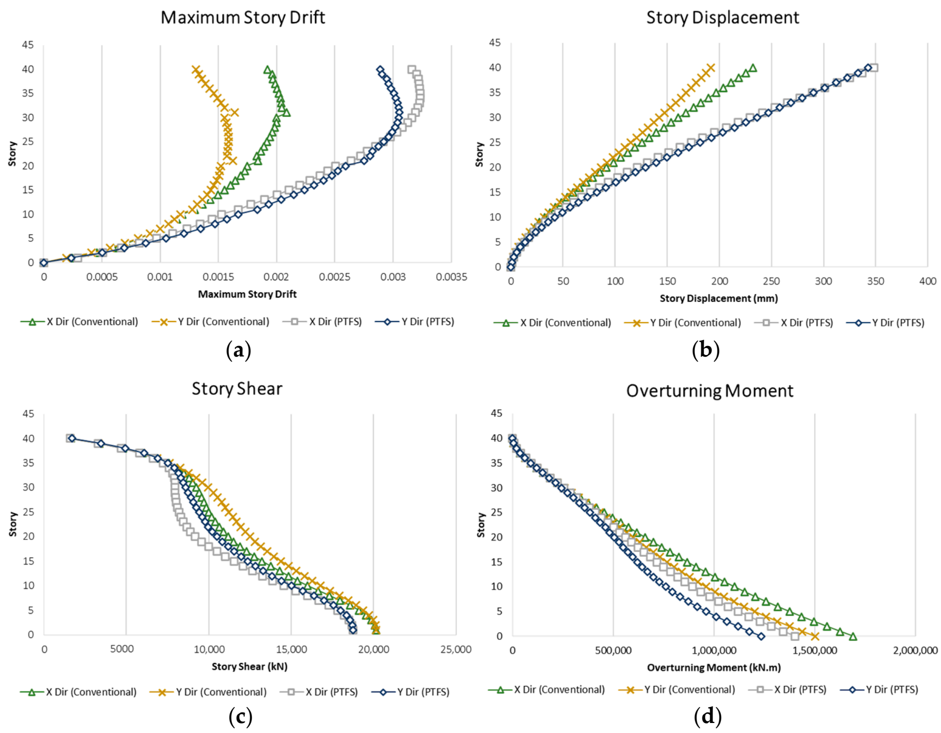


Figure 3. Structural responses of conventional and PTFS structures: (**a**) maximum story drift; (**b**) story displacement; (**c**) story shear; and (**d**) overturning moment.

On the other hand, the results of the structural response, obtained from the tendon layout variations, show that the structural responses to each variation of the tendon layout are very similar. This indicates that the variation of tendon layout does not affect the structural response of the PTFS structure. The slight differences between each variation could be the reason for the resemblance to the structural response. The final cross-section design of element members is shown in Table 5, for the conventional structures, and in Table 6, for the PTFS structures. Based on these results, the volume of materials and the cost analysis can be calculated.

Table 5. Design of conventional structures.

Element	Dimension (mm)			
	Floors 1–10	Floors 11–20	Floors 21–30	Floors 31–40
Secondary beam	300 × 600	250 × 500	250 × 400	250 × 400
Primary beam	450 × 900	450 × 900	450 × 900	400 × 800
Typical column	1500 × 1500	1200 × 1200	800 × 800	600 × 600
Column near Shear walls	1500 × 1500	900 × 900	800 × 800	800 × 800
Slab	Thickness: 150 mm			
Shear walls	Thickness: 500 mm			

Table 6. Design of PTFS structures.

Element	Dimension (mm)			
	Floors 1–10	Floors 11–20	Floors 21–30	Floors 31–40
Perimeter beam	600 × 900	600 × 900	500 × 800	500 × 800
Perimeter column	1200 × 1200	450 × 900	800 × 800	800 × 800
Typical column	1100 × 1100	900 × 900	750 × 750	500 × 500
Column near shear walls	1550 × 1550	1200 × 1200	900 × 900	850 × 850
Slab	Thickness: 200 mm			
Drop panel	Thickness: 350 mm			
Shear walls	Thickness: 500 mm			
Tendon	38.17 kg/m^3			

Based on the calculations of the material volume, the use of PTFSs can save the reinforcing steel material by 22.79%, save concrete material by 10.8%, and save formwork material by 22.54%. The comparison of the material volumes is shown in Figure 4. This shows that a reduction in the quantity and price of materials (including concrete and steel reinforcements) can be achieved. Regarding the costs, including the prestressing costs, the overall cost of the structure can be reduced by up to 6.15%, compared to the conventional structures with the reduction of up to IDR 31,101,210,944.34 from the total cost of the conventional structure IDR 505,510,579,800.68. This corresponds to the previous studies, which demonstrate that the PTFS can reduce reinforcement steel by nearly 70% and concrete material by 20% [17,18,20]. The cost calculation is based on the unit price for each item. The unit price is calculated for 2024, based on Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat (PUPR) Nomor 1 Tahun 2022 [34], as shown in Table 7. More often than not, the unit prices remain the same for both conventional and PTFS structures. The main difference in the PTFS structures is the addition of tendons. The unit price for the tendons has been considered in the material and installation costs.

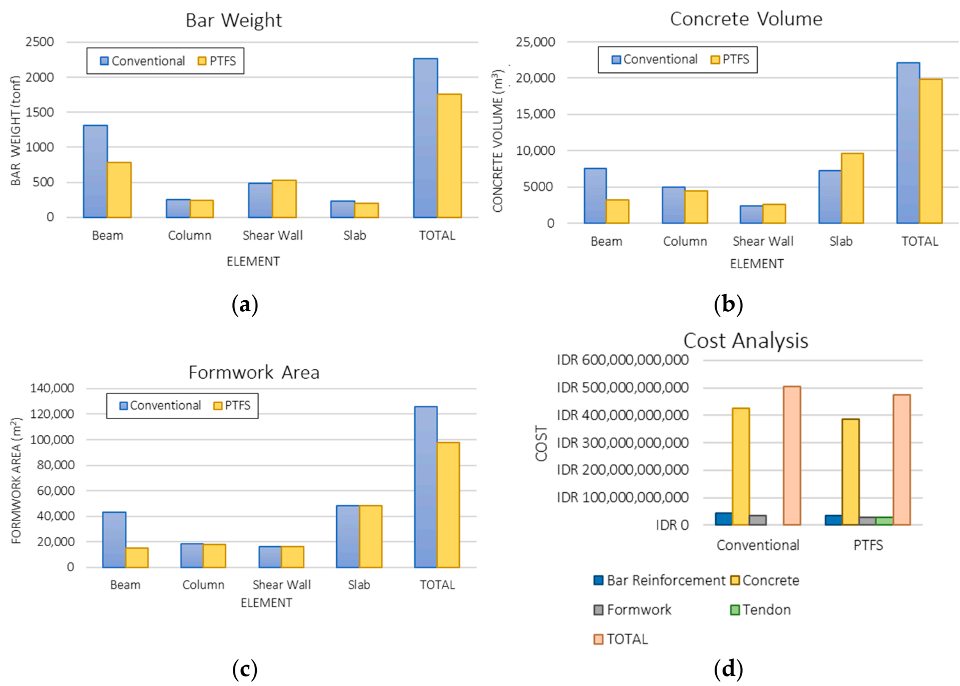


Figure 4. Comparison of conventional structures' and PTFS structures' (**a**) bar weight; (**b**) concrete volume; (**c**) formwork area; and (**d**) overall cost analysis.

Table 7. Unit price for work items.

Unit Work	Unit Price
Slab reinforcement/kg	IDR 19,839.80
Column reinforcement/kg	IDR 19,018.24
Beam reinforcement/kg	IDR 19,018.24
Shear wall reinforcement/kg	IDR 19,018.24
Column formwork installation/m^2	IDR 280,163.00
Beam formwork installation/m^2	IDR 267,067.32
Slab formwork installation/m^2	IDR 268,582.50
Shear wall formwork installation/m^2	IDR 274,094.83
Dismantle the formwork/m^2	IDR 11,385.00
Casting/m^3	IDR 1,673,606.50
Tendon/ton	IDR 73,910,500.00

4. Conclusions

The following conclusions were drawn based on the conducted analysis:

1. Structural response: Post-tensioned flat-slab structures exhibit higher values for the story drift and displacement, compared to conventional structures. On the other hand, conventional structures demonstrate greater values for the story shear and overturning moment. The structural response remains consistent across different tendon layout variations despite the slight differences between them.
2. Material savings: The use of the post-tensioned flat slab results in a significant reduction in materials, with a 22.79% reduction in reinforcing steel bars, 10.08% in concrete, and 22.54% in formwork.
3. Cost-Effectiveness: In terms of material, bar reinforcement installation, casting, and post-tensioned installation, post-tensioned flat slab structures prove to be more cost-effective than conventional structures. The overall structural costs are reduced by up to 6.15%, compared to conventional structures.

4. SGLR system: When designing high-rise buildings, particularly those combining post-tensioned flat slabs as part of the structural system, it is essential to consider the separated gravity lateral resisting (SGLR) system. This approach ensures that the flat slab is not designed to resist lateral loads. In the designing process, it is important to consider deformation compatibility in the analysis to ensure ductile flexural yielding in the structure system.

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