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The influence of the layout of shear walls on internal forces and horizontal displacements in an 18-story building

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Abstract: High-rise buildings are highly sensitive to horizontal loads. Therefore, any changes made to the arrangement, size, or shape of the shear walls will have significant effects on the strength and performance of the building. In this article, the author conducted an investigation on specific cases: walls located at the corner of the building, walls present in both directions, and reinforced concrete frames. The results of the analysis suggest that changing the placement of walls located at the four corners of the structure will significantly influence the bending moment, shear force, and axial force observed at the base of the columns. At the same time, it also affects the top displacement based on the direction of the main bearing of the structure. The survey results include diagrams showing the bending moment, the shear force, and the axial force in the main frame of the building. These values are then compared with each other at BoC in the main frame. It is evident that the bending moment and shear force values for Case 1 and Case 3 are significantly lower compared to Case 2. This suggests that Case 1 and Case 3 are the most favorable options for calculating and designing the structure of this high-rise building.
Keywords: *Building, Displacement, Floor slabs, Frame, Horizontal load, Structure, Walls.*

1. Introduction

Analysis of wind factors is essential when designing high-rise buildings (HRB). Researchers have conducted studies on the resistance of structures to wind and earthquakes by examining the effects of different wall arrangements. These arrangements include structures without rigid walls, structures with rigid walls placed in the center, and structures with rigid walls placed at the corners. Research has demonstrated that symmetrical constructions with rigid walls positioned in the center show superior response compared to constructions without rigid walls or with rigid walls placed at the corners. Contrary to expectations, when it comes to rigid asymmetric shear walls (SW) in construction, placing rigid walls at the corners results in the most favorable response. This contrasts with conditions where there are no rigid walls or where rigid walls are positioned in the center [1]. It is essential to conduct a thorough assessment of the seismic response of the structure due to the significant impact that the characteristics of these SWs have on the overall response of the building's structural system. The study determined that the reconfiguration of the SWs significantly influences both the story's shear capacity and the building's top displacement [2]. Horizontal loads are of significant importance in the structural design of HRB. Rigid walls are a type of vertical component commonly employed in building structures to meet the required horizontal stiffness requirements. The objective of the investigation [3] was to investigate the behavior of HRBs with rigid load-bearing walls in terms of their location and arrangement to provide effective resistance to lateral loads. Specifically, the study focused on understanding the response of these buildings to horizontal weight. The results of the research show that centrally located SWs in the form of cores demonstrated superior performance in resisting lateral loads. The displacement at the top (DT) of a building is approximately 2.5 times less than the DT floor of a building lacking rigid walls. Positioning SWs at corners minimizes their effectiveness. Based on the results of research [4], the use of

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SWs symmetrically and in shorter spans within the chosen structural option has been shown to result in reduced displacement and horizontal behavior, compared to structures that employ SWs in different directions. The workings of an HRB structure can be compared to those of a console that has an appropriate size ratio. However, the structure of a bending moment (BM) member is different from that of a typical column structure. The bending of the building is not limited to just a bending shape but can also involve a shear form or a combination of BM and shear force (SF). In addition, it is worth noting that these shapes can occur not only due to horizontal bending but also as a result of torsion or flexion-torsion [5]. When subjected to a horizontal load, the structure experiences horizontal displacement (HD). There will be different displacements on each cross section of the building at different points. The analytical results of B.B. Khansi have shown that torsion has a significant influence on HD [6]. Both Japanese and American wind load calculation standards mention the torsional component of the wind load [7, 8]. Vietnam commonly designs earthquake-resistant reinforced concrete frame structures with low to medium levels of elasticity. There is a significant difference in the calculation process between earthquake-resistant reinforced concrete frames with low elasticity levels and those with medium elasticity levels. Elastic diagrams analyze reinforced concrete frames with low elasticity, while plastic joint diagrams analyze frames with medium elasticity. The latter case forms plastic joints at the ends of the beams and columns [9]. The impact of horizontal loads has a significant effect on multi-story buildings. As the height of a building increases, the impact of horizontal loads increases, resulting in a more significant displacement of the structure. The challenge of increasing horizontal stiffness and reducing displacement always confronts designers. The structural system is continuously evolving to address this issue. In modern times, the use of a combined frame-wall system has proven to be an effective structural solution to improve the horizontal stiffness of a building [10].

In Vietnam, there are guidelines available to calculate the structures of HRBs [11, 12]. The author carefully looked at how HRB models work and how solid basement SWs affect the building's top movement. Buildings with and without solid basement SWs were looked at, as well as those with and without different basement heights. The study looked at how well the structure system worked, with a focus on the HD at the very top. A computer study was done using the Etabs to find the BM, SF, and axial force (AF) at the base of the column (BoC). An investigation was conducted for two different scenarios, one of which had SWs in the basement while the other did not. The research work also considered modifications in the basement's height [13]. It is important to note that wind loading has a considerable influence on the stiffness of a structure, which leads to large displacements, particularly at the highest levels. Attempting to investigate these consequences turned out to be a challenging area of research.

When compared to loads that were applied to the geometric center of the structure, the research investigated the effects of wind loads on columns that were positioned inside the frame of the building. The paper thoroughly investigated the impact of these differences on the BM, SF, and AF at BoC in the structural frame. Furthermore, it conducted an analysis of the HD that occurred on different levels of two buildings, one of which had seven stories and the other of which had twenty-five floors. When it comes to the design of buildings, whether they are considered high-rise or low-rise, it is essential to assign wind loads to the geometric center of the building [14]. When it comes to the design of the structure of a HRB, it is essential to take into account both the load-bearing capacity of the whole building as well as the need to limit HD at the top of the building. The author used the Etabs programme in order to carry out an investigation and comparison of the HD that occurred at the peak of a structure. In the course of the research, two distinct structural systems were investigated: the frame system, which included columns, beams, and floors; and SWs, which were made entirely of reinforced concrete walls. Following Vietnamese standards on loads and effects, especially Vietnam Standard (TCVN) 2737:2023 [15], the study was carried out after the standards were established. The structure's centroid was subjected to wind loads that were applied to it. According to the conclusions of the study, the HD that occurs at the top of high-rise structures has a substantial influence. Furthermore, studies have demonstrated that the SW system outperforms the frame system in terms of HD value [16]. Additionally, you can use structural software like Etabs or Sap2000 to calculate the displacement the structure has undergone. Global positioning

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system technology can measure the HD of an HRB. Global positioning systems (GPS), sometimes known as GPSs, were first designed for use in military applications, such as navigation and single-point locating. Generally, non-military objectives, particularly those involving baseline measurements, have pioneered the early applications of geodetic measurements using differential techniques. An alternative method for measuring displacements in HRB systems involves the use of GPS technology. This article presents two tests that evaluate the precision of GPS measurements. In addition to this, the book offers an analysis of the capability of the GPS to monitor minute movements of the Stuttgart television tower and the industrial chimney of the Opole power plant when there are only light winds present [17]. It is very necessary to perform precise monitoring of HD in order to conduct an accurate assessment of the structural health of HRBs.

The purpose of this work is to offer a unique method for estimating the HD of HRBs by integrating measures of strain and acceleration. Initially, the quasi-static component of structural displacement was derived by making use of the longitudinal stresses that were observed, according to the assumptions that are outlined in the classical beam theory. In order to estimate the resonant displacement, which was found by using a finite impulse response filtering technique based on the observed acceleration, the displacement that was acquired from the quasi-static analysis was merged with both of these displacements. Because of this, it was possible to compute the entire horizontal displacement. Through the use of numerical studies, the effectiveness of the proposed method is investigated. In these studies, two cantilever beams with distinct sectional shapes are utilized to validate the technique's capacity to accurately estimate horizontal displacements in the presence of varying noise levels in the signals and a number of measurement points. Next, a field measurement validation study is provided, which proves the practicability and accuracy of the suggested approach for calculating the HD of tall structures under typhoon circumstances. This research examines the results of the proposed technique. The research focuses on a building that is 600 meters in height [18].

Torsional wind loads on rectangular, tall structures were evaluated in a boundary wind tunnel using five models with varied rectangular cross sections. The results of the tests were used to examine Root-mean-square (RMS) force coefficients, power spectrum densities, and torsional wind load vertical correlation functions. Formulas based on side ratios were presented to suit the test results. By comparing formula results to wind tunnel observations, the suggested formulas were shown to be reliable. The given formulas are used to calculate dynamic torsional wind loads on tall rectangular structures in urban terrain. An actual project confirmed the expression. Simple expressions and formulas [19] can estimate the frequency domain of wind-induced torsional response on tall rectangular structures.

The wind tunnel tested nine models with various rectangular cross sections to study wind forces on tall structures [20]. Brief data was reported. This article analyzes local wind forces on tall structures utilizing mean and RMS force coefficients, power spectral density, and spanwise correlation and coherence. Elevation, aspect ratio, and side ratio affect bluff body flow and local wind forces, according to the report. Integrating local wind forces yields overall loads and base moments. Two wind tunnels' high-frequency force balances are compared.

The wind is complicated, with several eddies of varied sizes and rotational properties flowing relative to the earth. These eddies generate wind gustiness, creating a complicated, shifting flow. The mean wind vector and fluctuation components make up the wind vector at any position. Height, approaching terrain, and geography affect this system's components. Wind pressure affects structural surfaces. Wind pressure may cause structural collapse, especially shear and BMs. This research analyzes wind load on a 15-story HRB using European standard (EN) 1991-1-4 and Malaysian standard (MS) 1553:2002. The modeling findings show that when wind speed rises, story shear and moment increase. EN 1991-1-4 simulation results are greater than MS1553:2002 simulation results [21].

Additionally, there are design standards that are used in the calculation of HRBs, such as [15, 22-24].

The aforementioned authors' research has significantly contributed to the development of suitable conditions for calculating and designing HRB structures. However, previous studies have not specifically investigated the relationship between BM, SF, AF at BoC, and DT of the structural system in relation to the arrangement of rigid walls during impact and the use of load. The author of this article investigates the issue in combination, providing a detailed examination of the conditions necessary to efficiently calculate, design, and arrange rigid walls. This study investigated four specific cases. Case 1 includes a symmetrical arrangement with walls at the corners of the building in the X direction. Case 2 also presents a symmetrical arrangement, but with walls at the corners of the building in the Y direction. In Case 3, the walls are symmetrically arranged in both directions at the core. Finally, Case 4 presents a reinforced concrete frame model that is symmetrical in both directions. The values of AF, BM, SF, and HD have been determined on the floors and at the top of the building.

1.1. Research Significance

Research has been conducted to investigate the impact of reinforced concrete walls on the structural integrity of HRBs as well as the optimal arrangement of these walls. Conducting an investigation of the effects is essential, including both scientific and practical aspects.

1.2. The Objective of the Current Study

In order to determine the BM, SF, and AF at BoC, as well as the HD at the top of the structure, it is necessary to conduct a survey. All of these forces should be measured on the same plane. Make certain that the load that is being applied does not change at any point throughout the survey. In light of the findings, please share your thoughts and evaluations about the effects of rearranging the walls in their current positions.

2. Materials and Methods

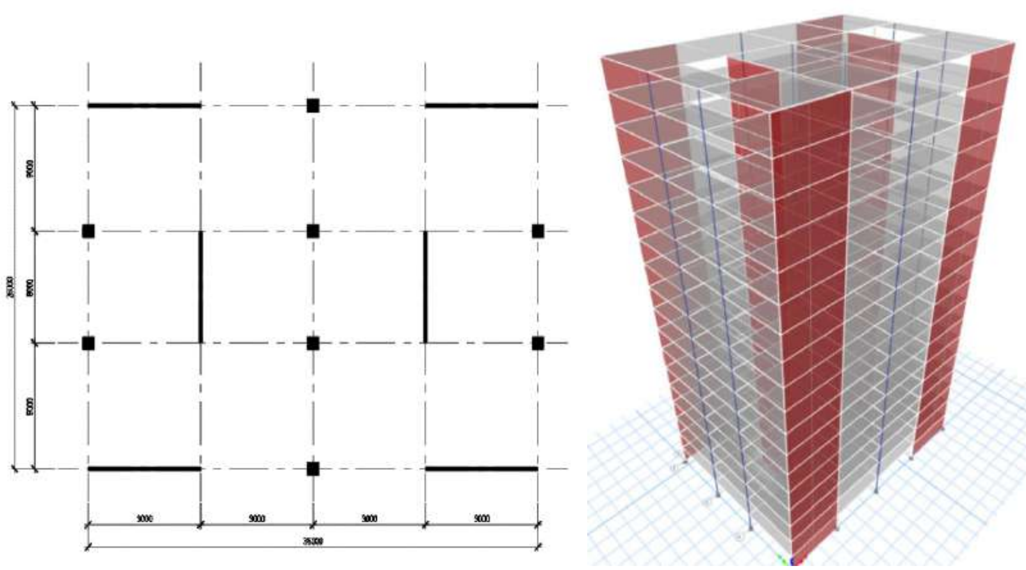
The building has been surveyed in the following cases:

Case 1: Symmetrical arrangement: walls at the corners of the building in the X direction, shown in Figure 1a.

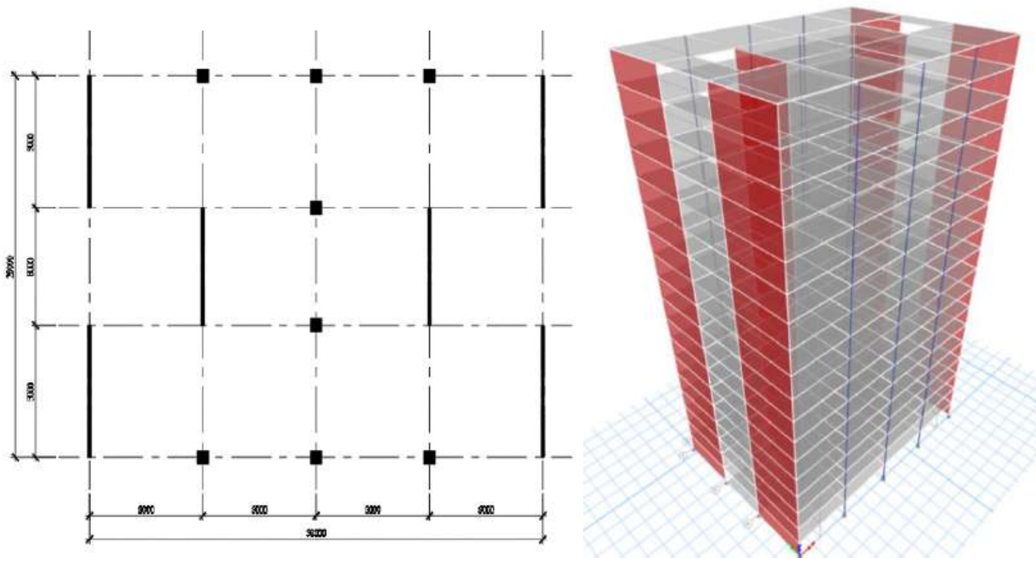
Case 2: Symmetrical arrangement: walls at the corners of the building in the Y direction, shown in Figure 1b.

Case 3: Arrange walls symmetrically in both directions at the core, as shown in Figure 1c.

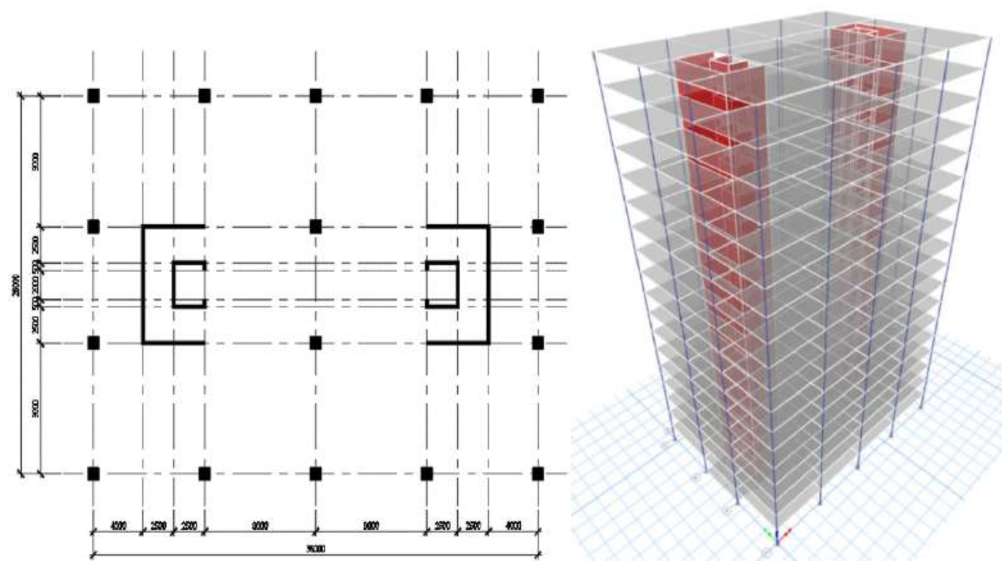
Case 4: The reinforced concrete frame model is symmetrical in both directions, as shown in Figure 1d.



a) Case 1, Symmetrical arrangement, walls at the corners of the building in the X direction.



b) Case 2, Symmetrical arrangement, walls at the corners of the building in the Y direction.



c) Case 3, Arrange walls symmetrically in both directions at core.

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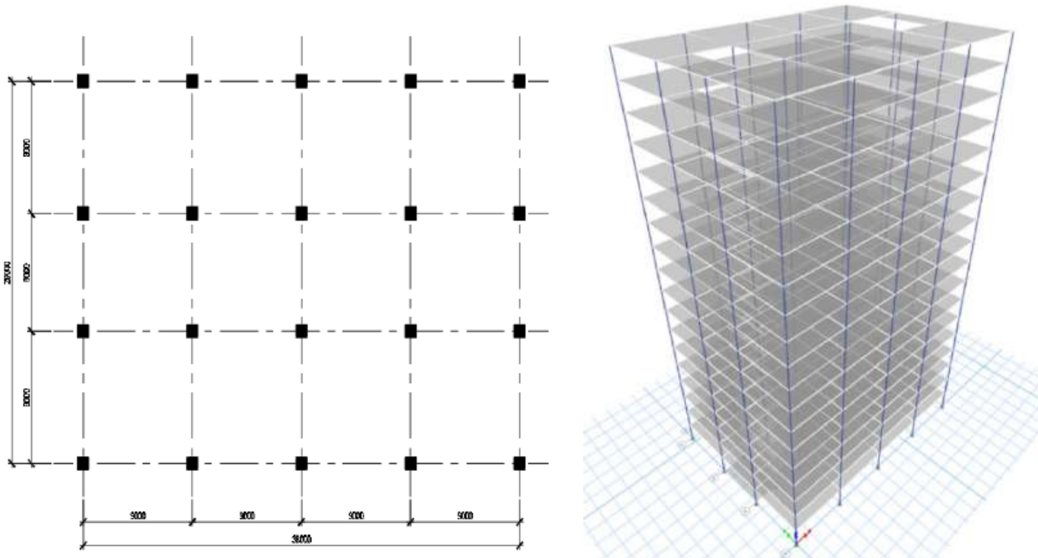

d) Case 4, Reinforced concrete frame model is symmetrical in both directions.

Figure 1.
Plan and 3D model of the cases surveyed.

The building has a total of 17 floors and 1 basement. A reinforced concrete SW frame structure constructs the building, designed to withstand earthquake loads. The design includes consideration for the following parameters:

- The floor plan of the building is 26m×36m, 62.8m high. There are 4 spans in the X direction, each measuring 9m, and 3 spans in the Y direction, also measuring 9m each.
- The height of each floor is 3.5m (from floor 1 to floor 18), and the basement is 3.3m high (from the base to floor 1).
- Assume that a brick wall with a thickness of 200mm is built on all beams (the roof floor does not have brick walls).
- The deadload on the floor is 2 kN/m^2 (The load applied to the floors is distributed as a force over a given area.)
- The liveload that is acting on the floor is 2.5 kN/m^2, the live load that is acting on the roof floor is 1 kN/m^2, and the dead load that is being imposed by the brick wall on the beam is 1.5 kN/m.
- Select sizes: floor that is 0.15 m thick, beams that are 0.3×0.6m, and SWs that are 0.25 m thick and made of reinforced concrete.
- Concrete with grade B25 and AII steel group are the materials that are needed.

Table 1 displays the sizes of the columns. The columns of the building gradually increase in cross section as they approach the foundation.

Table 1.
Sizes of the columns.

Base ÷ Story 3	**Story 4 ÷ Story 7**	**Story 8 ÷ Story 11**	**Story 12 ÷ Story 15**	**Story 16÷Story 18**
0.9×0.9m	0.8×0.8m	0.7×0.7m	0.6×0.6m	0.5×0.5m

Wind loads that are both static and dynamic on the building, shown in Table 2, and the wind load is assigned to the geometric center of the structure, as shown in Figure 2.

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Table 2.
Wind loads.

Story	Static load of win (kN)		Dynamic load of win (kN)	
	X direction	Y direction	X direction	Y direction
Story 18	192.2	316.2	84.2	136.1
Story 17	190.2	312.8	84.2	128.7
Story 16	188	309.3	73.9	103.9
Story 15	185.7	305.6	63.6	107.5
Story 14	183.4	301.6	63.6	109.7
Story 13	180.8	297.5	53	95.5
Story 12	178.1	293	53	105.3
Story 11	175.2	288.2	42.6	98.2
Story 10	172	282.9	32.2	98.8
Story 9	168.5	277.3	32.2	86.4
Story 8	164.7	271	21.4	86.4
Story 7	160.4	264	21.4	76.3
Story 6	155.6	256	10.7	66.8
Story 5	149.9	246.6	10.8	48.5
Story 4	143.1	235.4	10.8	38.3
Story 3	134.3	220.9	3.4	13.5
Story 2	121.6	200.1	1.2	5.8
Story 1	35.4	58.2	0	0

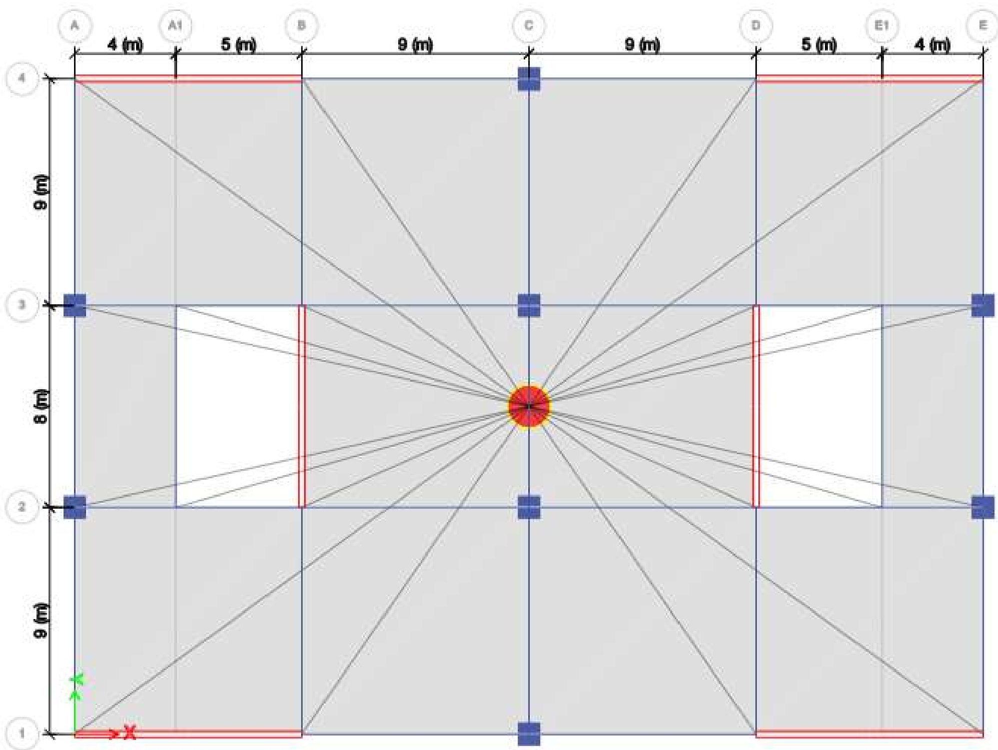


Figure 2.
Wind loads are assigned to the geometric center of the structure.

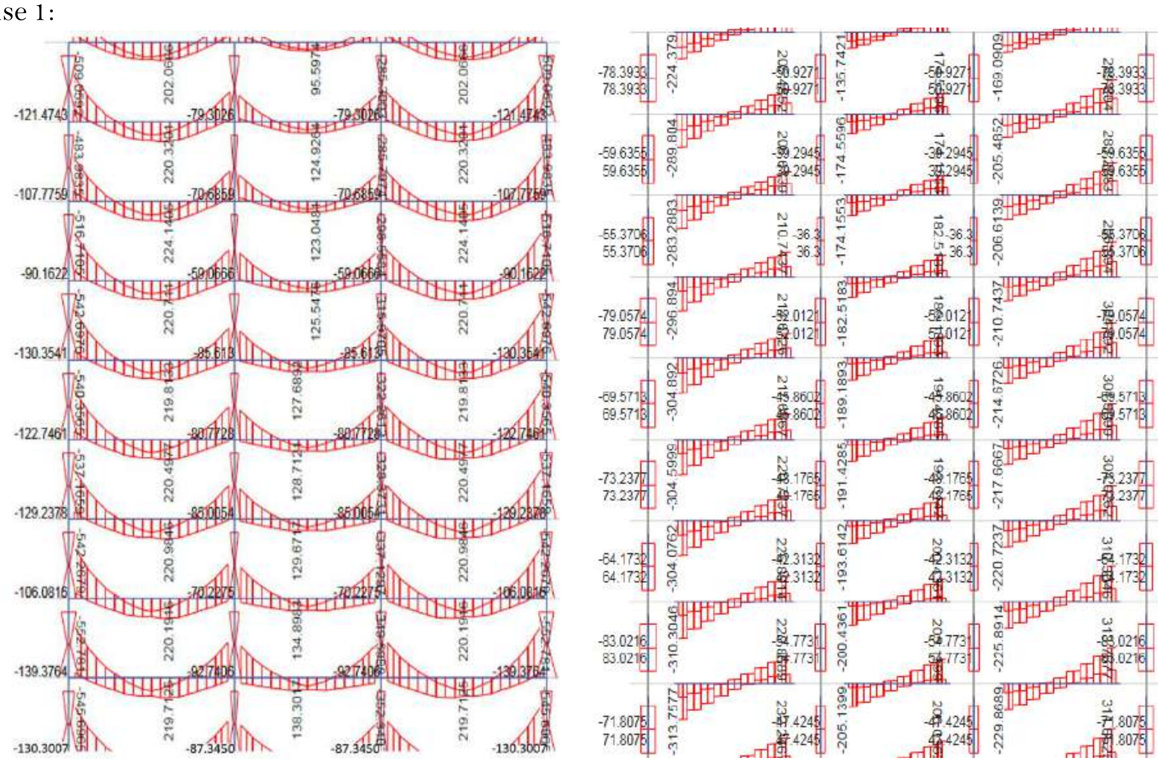
Charge combination:
COMB 1: 1 DEAD + 1 LIVE
COMB 2: 1 DEAD + 1 WINX

COMB 3: 1 DEAD + 1 WINXX
COMB 4: 1 DEAD + 1 WINY
COMB 5: 1 DEAD + 1 WINYY
COMB 6: 1 DEAD + 0.9 LIVE + 0.9 WINX
COMB 7: 1 DEAD + 0.9 LIVE + 0.9 WINXX
COMB 8: 1 DEAD + 0.9 LIVE + 0.9 WINY
COMB 9: 1 DEAD + 0.9 LIVE + 0.9 WINYY
ENV: COMB 1+ COMB 2+…+ COMB 9

3. Results and Discussion

The envelope diagram of the BM, SF, and AF of the C-axis frame, case 1, shown in Figure 3

Case 1:



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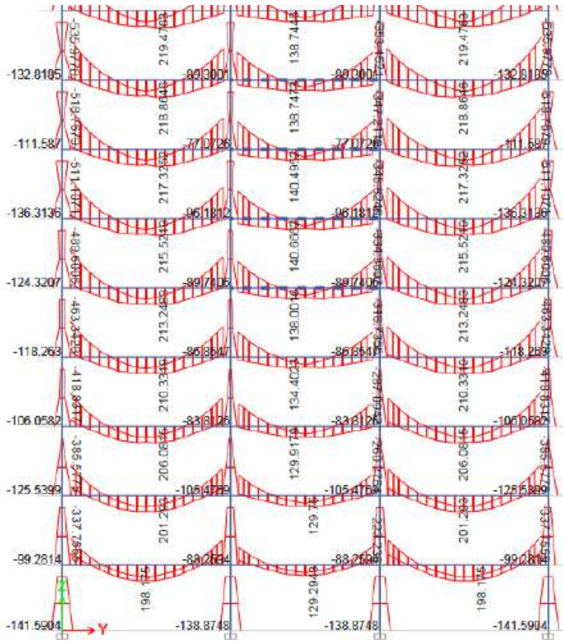
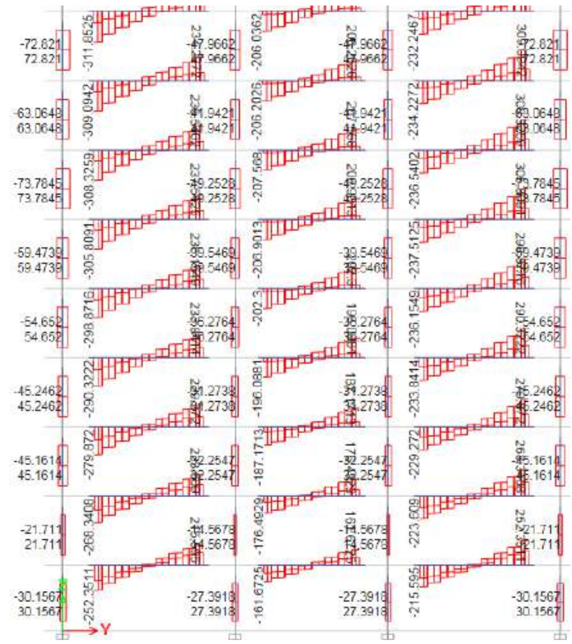
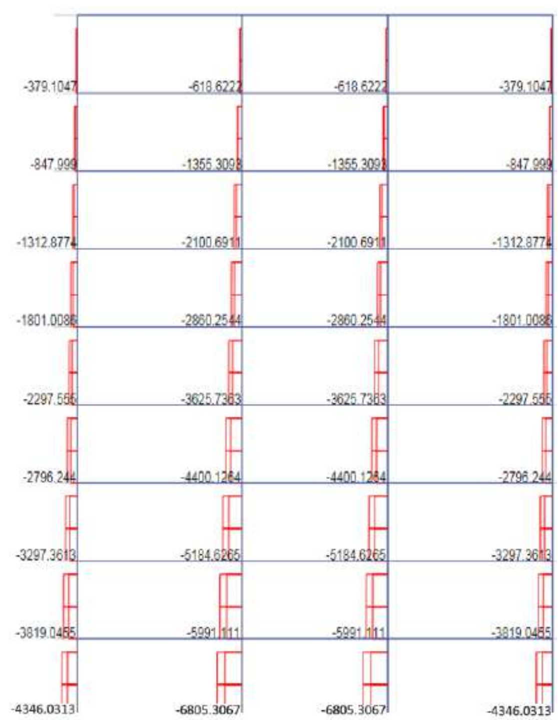


a) BM (kNm)



b) SF (kN)



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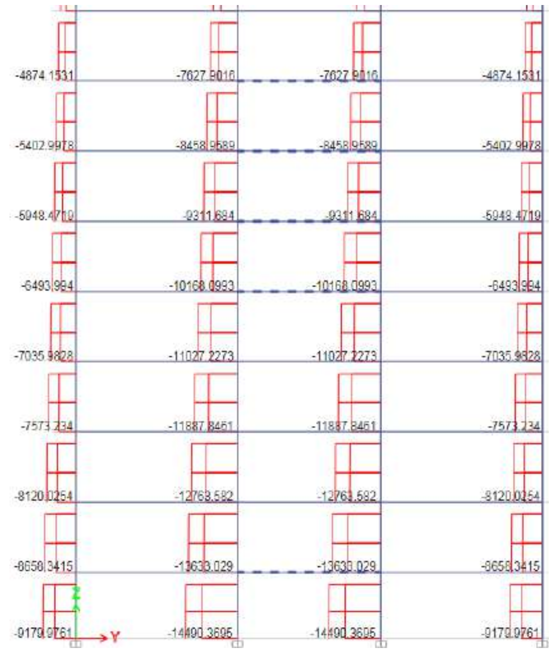


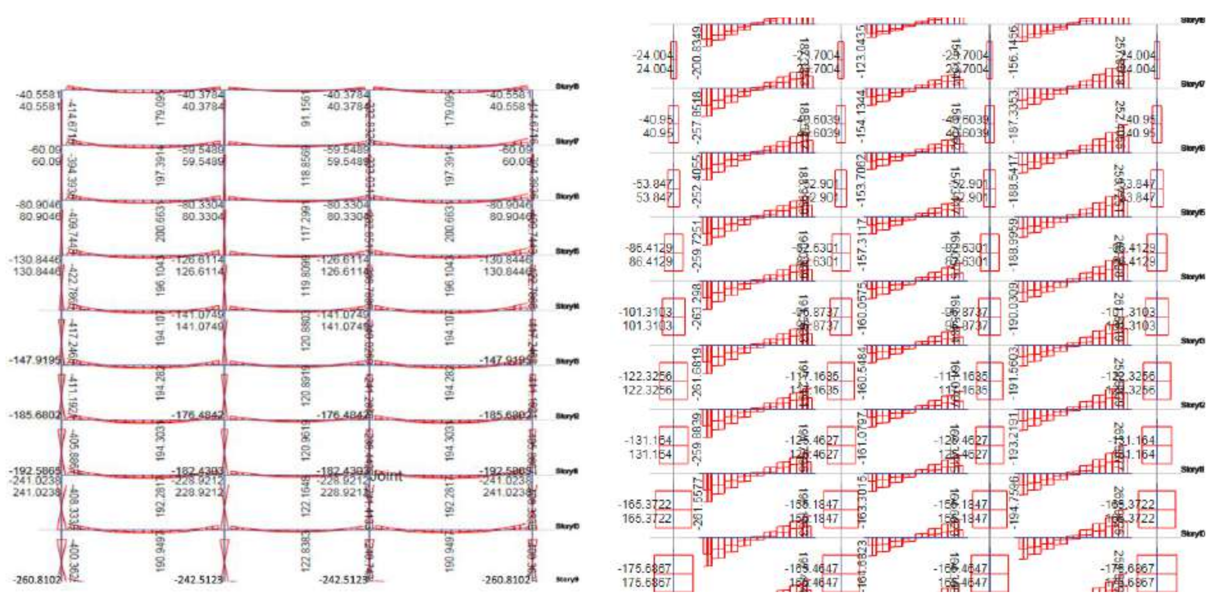
c) AF (kN)

Figure 3.
The envelope diagram of the BM, SF, and AF of the c-axis frame, case 1.

The survey results for Case 1 in the C-axis frame indicate that the maximum AF at BoC is 14490 kN, the BM is 141 kNm, and the SF is 30.2 kN. Case 1 demonstrates that the BM and SF values are quite minimal.

The envelope diagram of the BM, SF, and AF of C-axis frame, case 2, is shown in Figure 4.

Case 2:



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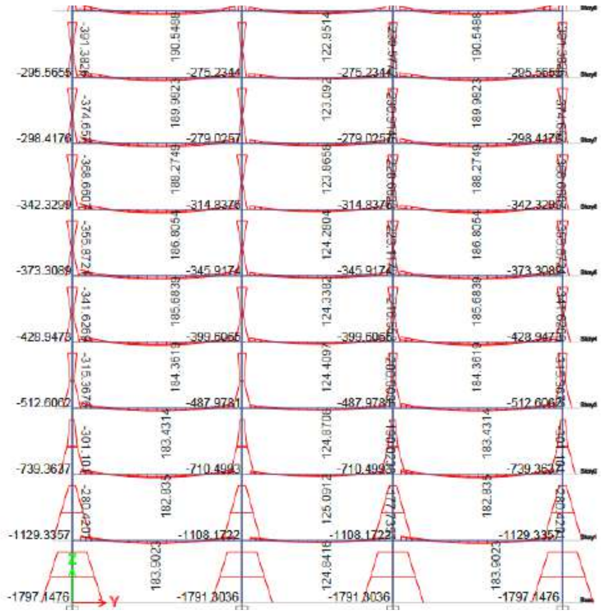
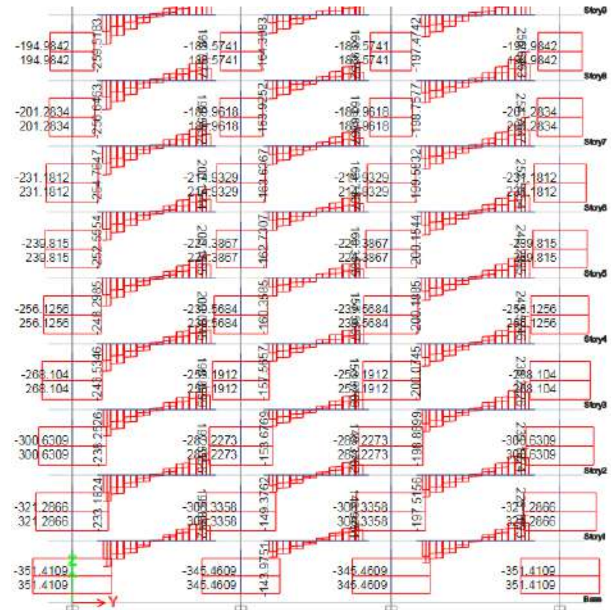
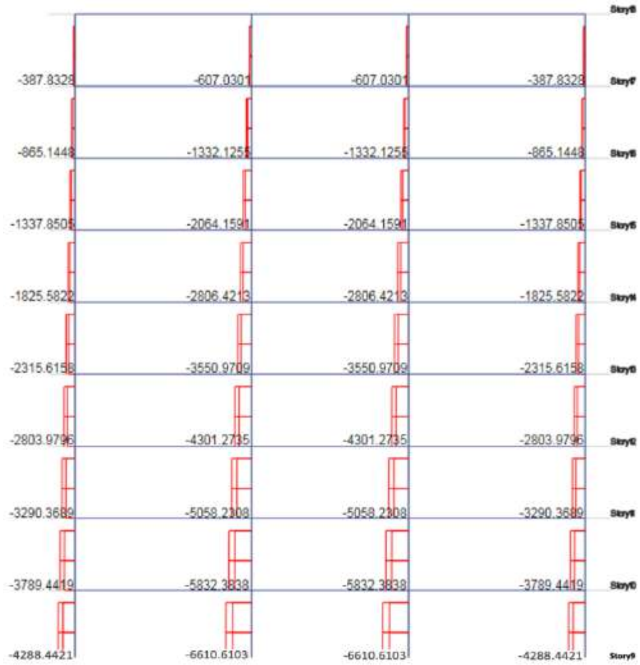


a) BM (kNm)



b) SF (kN)



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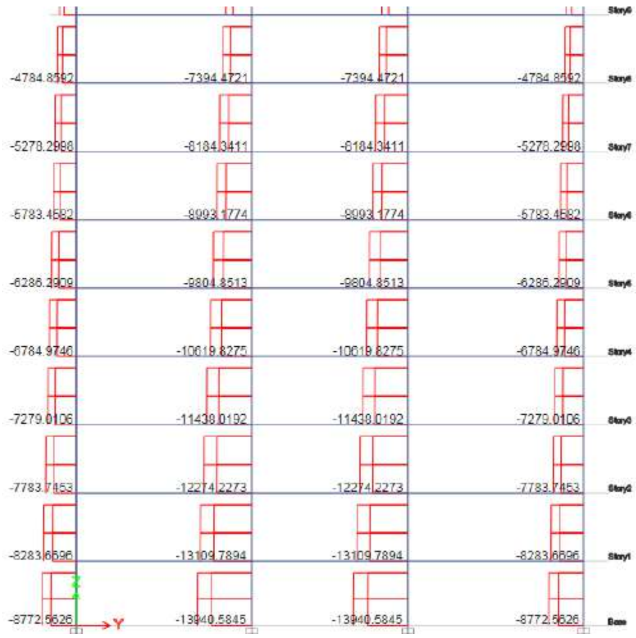


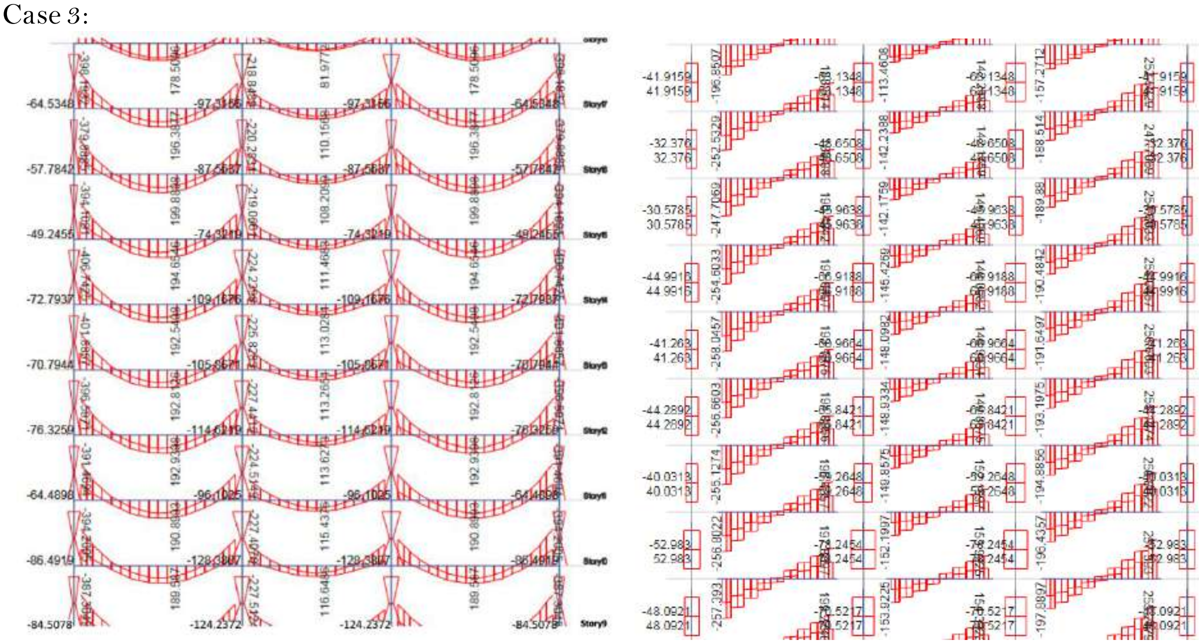
c) AF (kN)

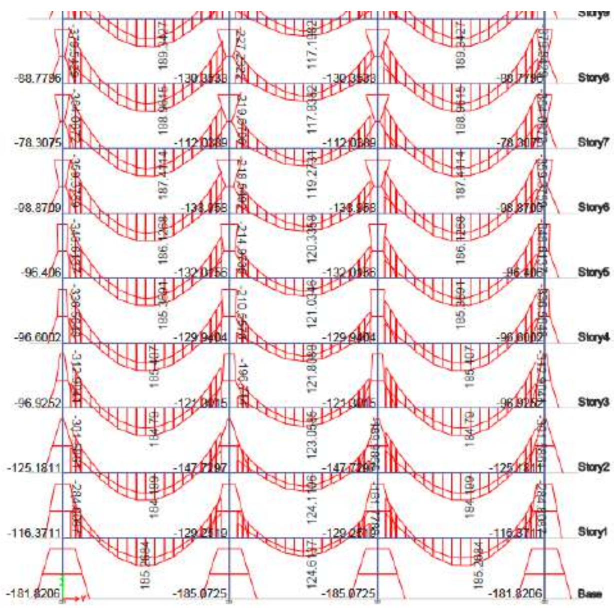
Figure 4.
The envelope diagram of the BM, SF, and AF of C-axis frame, case 2.

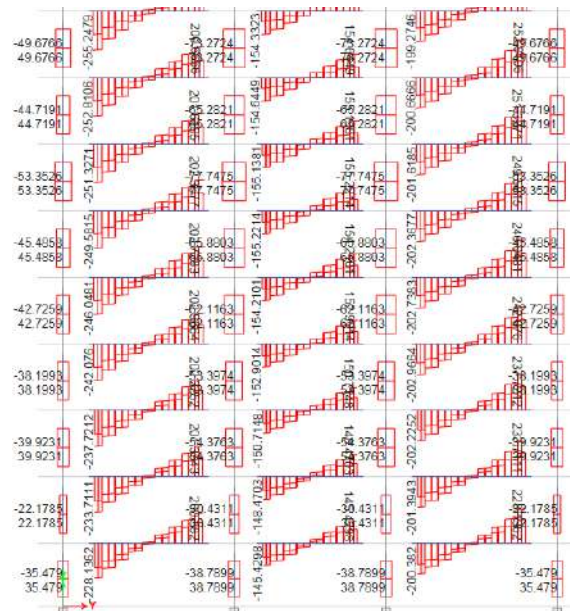
Case 2 shows that the AF at BoC remains relatively stable, with a value of 13940 kN, compared to Case 1. On the other hand, Case 2 experiences a substantial increase in the BM and SF, exceeding 10 times the values observed in Case 1. This case significantly influences the choice of structure type in the project's structural design.

The envelope diagram of the BM, SF, and AF of C-axis frame, case 3, shown in Figure 5

Case 3:

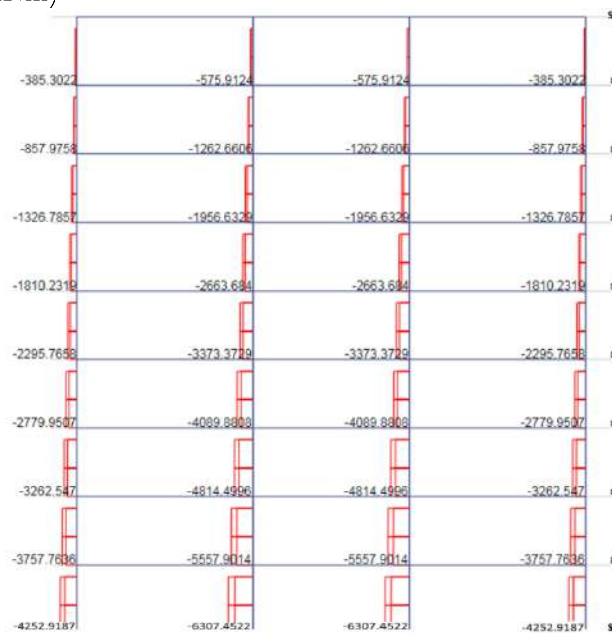






a) BM (kNm)

b) SF (kN)



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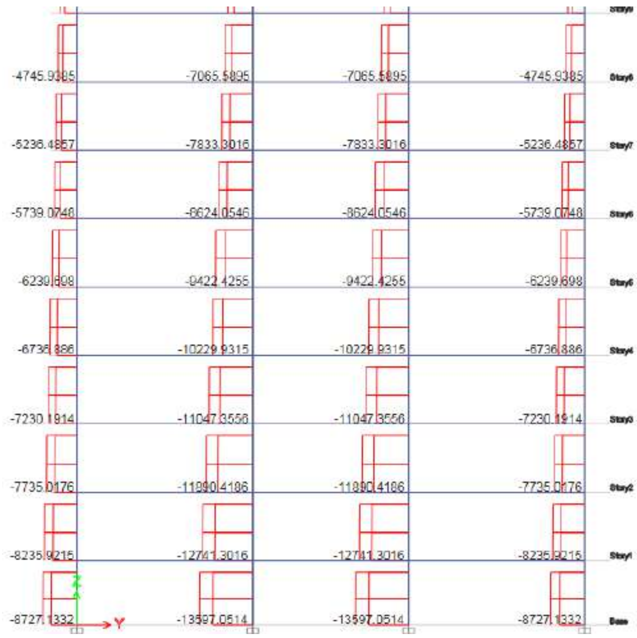


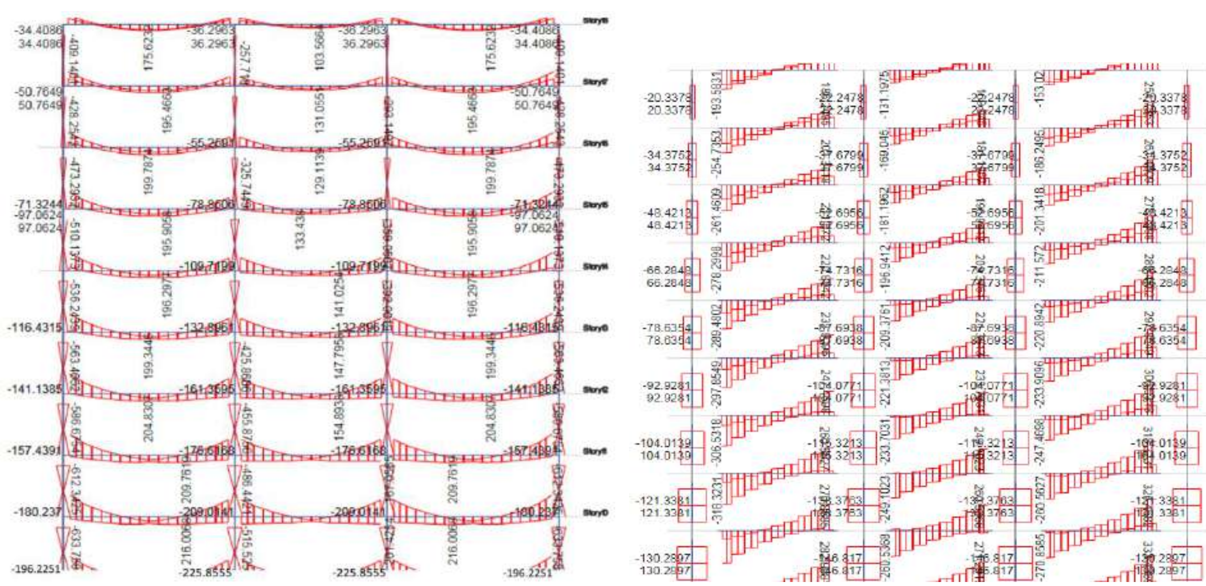
c) AF (kN)

Figure 5.
The envelope diagram of the BM, SF, and AF of C-axis frame, case 3.

The envelope diagram of the bending moment, SF, and AF of C-axis frame, case 4, is shown in Figure 6.

For Case 3, the AF is 8727 kN, which is approximately 40% lower than in Case 1 and Case 2. Furthermore, the BM and SF in this case closely resemble those in case 1, with values of approximately 185 kNm and 38.8 kN, respectively. Based on the analysis of these three cases, it becomes clear that Case 3 offers a structural solution that effectively addresses AF, BM, and SF. This makes it a viable option for design engineers to consider.

Case 4:



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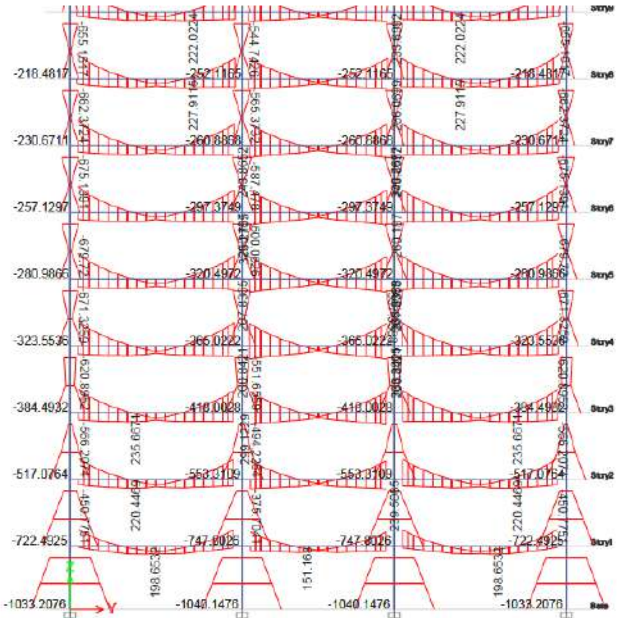
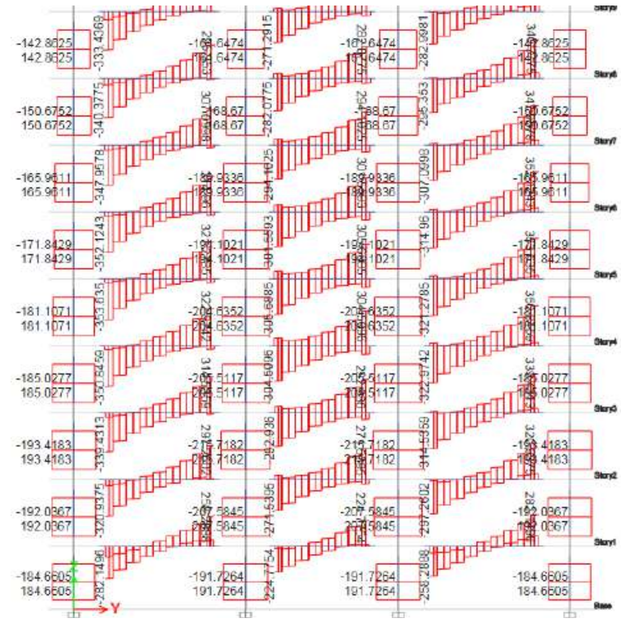
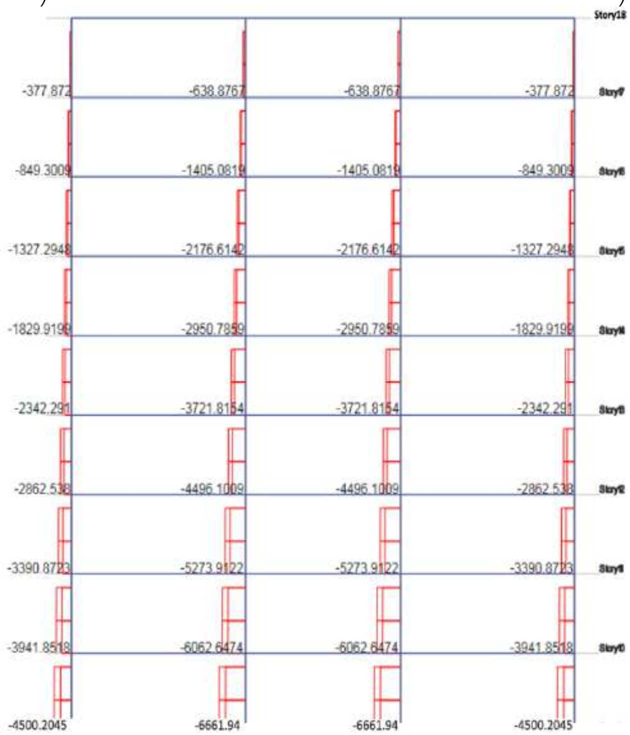


a) BM (kNm)



b) SF (kN)



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c) AF (kN)

Figure 6.
The envelope diagram of the BM, SF, and AF of C-axis frame, case 4.

Case 4 shows an AF that is consistent with Case 1 and Case 2. Compared to Case 1 and Case 3, Case 4 is five times larger.

In this analysis, we will compare the values of BM, SF, and AF at BoC in four different cases of the C-axis frame, shown in Figure 7.

a) BM (kNm) b) SF (kN)

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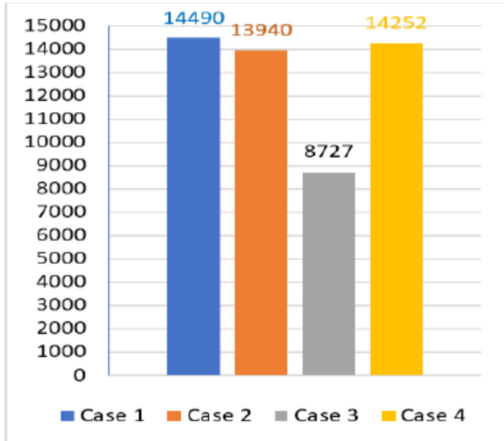
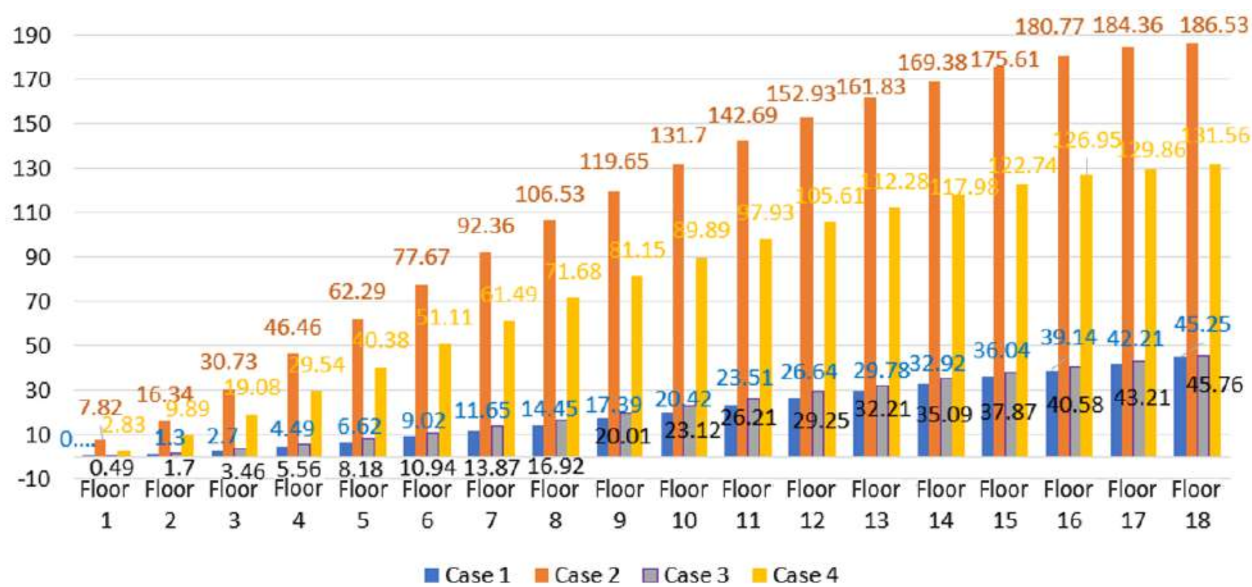


c) AF (kN)

Figure 7.
The four investigated cases at BoC.

Comment: In Figure 7a and 7b, it is observed that the BM and SF values for Case 1 and Case 3 are 10 times lower than those for Case 2. Case 2 shows significantly high moment and SF values. This suggests that Cases 1 and 3 are the preferred choices to calculate and design the structure of this HRB. In this project, the column is considered the most important structure. Figure 7c shows that Case 3 shows the lowest AF value. This means that Case 3 is the most optimal choice for the purposes of calculation and design. Case 3 in Figure 1c represents a situation where the walls are placed in close proximity to the geometric center of the building. Additionally, people commonly use walls to house elevators and/or stairs.

Figure 8 illustrates the displacement at the building floors for each of the four cases the C-axis frame investigated.



a) X-direction (mm)

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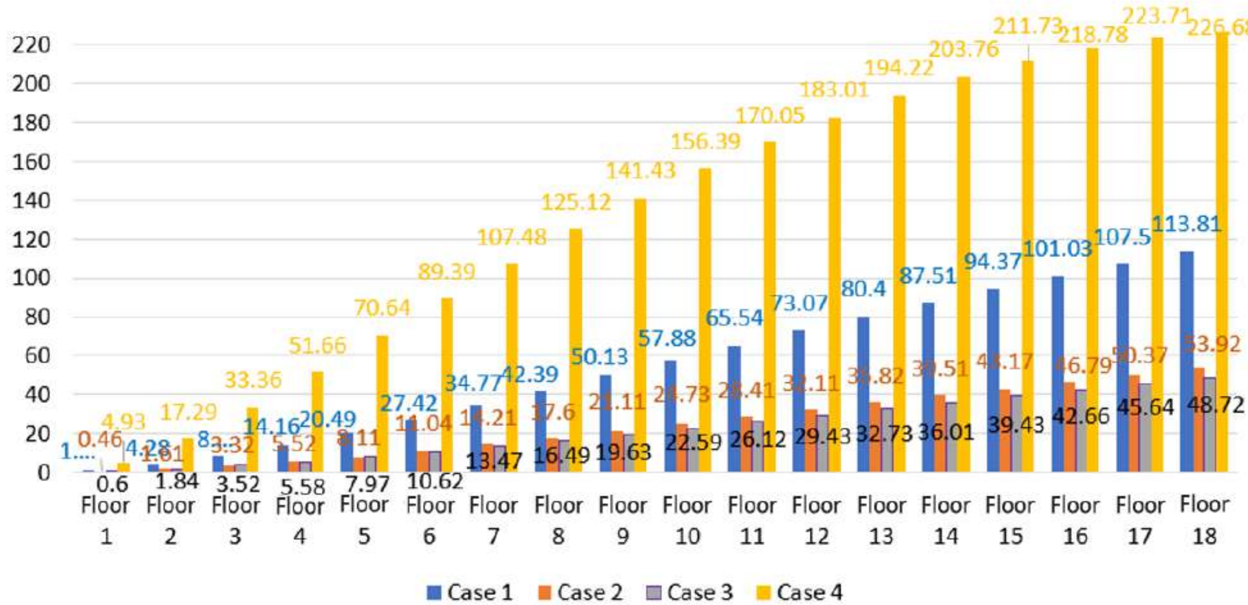

b) Y-direction (mm)

Figure 8.
Displacement on the floors of the building in the X direction and the Y direction.

When analyzing HRBs, it is important to evaluate and compare the AF, BM, and SF results. The HD at the top of the building must also meet other conditions, with a value of h/500=125mm, as specified in the standards: TCVN 5574:2018 and TCVN 2737:2023 [20, 21]. The height from the base of the first-floor column to the top of the building is denoted by h=62.8m.
As per TCVN 5574:2018 and TCVN 2737:2023:

- In Case 1, the value of f_u is calculated to be $f_u = \sqrt{{f_x}^2 + {f_y}^2}$ =122mm, which is less than $[f_u] =$ 125mm. This case successfully meets the requirement for HD at the top of the building.
- In Case 2, the value of f_u is calculated to be 194mm, which is bigger than $[f_u] = 125$mm. This case does not meet the requirement for HD at the top of the building. In this case, it is not possible to perform structural design.
- In Case 3, the value of f_u is calculated to be 66mm, this value is only half of $[f_u]$=125mm. The result additionally suggests that it is possible to increase the height of the building or decrease its stiffness.
- In case 4, the value of f_u is calculated to be 262mm, which is bigger than $[f_u] = 125$mm. This case does not meet the requirement for HD at the top of the building. In this case, it is not possible to perform structural design.

Comment: In Figure 8a and 8b, it can be seen that Case 3 shows the lowest displacement values on both floors and the top of the building. This result matches the observations made in Figure 7a, 7b, and 7c. The average HD value of Case 3 is five times lower than that of the other cases. Case 3 is considered the most optimal and highly recommended in the structural design of HRBs. The project has met the HD limit for multistory buildings, as stated in TCVN 5574-2018.

4. Conclusions

On the basis of the results of the study, the following conclusions can be drawn:

1. Based on the analysis of the four cases surveyed, it is evident that Case 3 shows the lowest values for various factors, including the BM, the SF, the AF, and the DT of the structure. Therefore, we recommend considering Case 3 in the structural design of multi-story houses. The results of the

study suggest that the placement of SWs in the core of the building offers the most optimal solution. Additionally, this location proves to be highly convenient for arranging the lift position.
2. Based on the results of the analysis, it is evident that affecting the position of the hard walls at the four corners of the building will significantly affect the internal force created on BoC of the load-bearing structural system of the building. Simultaneously, it changes the top displacement based on the primary carrying direction of the structure. Connecting the hard walls to form a symmetrical hard core enhances the structure's stiffness. This, in turn, leads to a significant reduction in internal forces and top displacement within the structural system.

Nomenclature:
DEAD = Dead load
LIVE = Live load
WIN = Win load
COMB = Combination
ENV = Envelope
HRB = High-rise buildings
SW = Shear walls
BM = The bending moment
SF = The shear force
AF = The axial force
HD = The horizontal displacement
DT = Displacement at the top
BoC = Base of the column
GPS = Global positioning systems
RMS = Root mean square
MS = Malaysian standard
EN = European standard
TCVN = Vietnam standard

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Competing Interests:
The author declares that there are no conflicts of interests regarding the publication of this paper.

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