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Corner Steel plate-Reinforced Core Wall System

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Abstract

For better structural performance and constructability, a new composite core wall system using steel plate columns at the corners of the core section was developed. Using the proposed core wall, nonlinear section analysis and 3-dimensional structural analysis were performed for the prototype core wall section and super high-rise building, respectively. The analysis results showed that, when compared to traditional RC core wall case, the use of the corner steel plate columns provided better structural capacity, which allows less wall thickness and re-bars. Further, due to such effects, the construction cost and time can be reduced despite the use of steel plate columns.

Keywords: Steel plate columns, Composite core wall, Outrigger, Core wall thickness

1. Introduction

To resist large wind load and earthquake load in high-rise buildings, RC core walls are frequently used, due to the good structural performance and economy. However, for better structural performance and constructability, such RC core wall system needs to be improved in the following aspects.

1) To resist the large wind load and earthquake load, a number of large diameter-reinforcing bars are used, which requires huge labor work in the construction. More importantly, due to the limitations of re-bar size and spacing, the re-bars are uniformly placed along the wall length. Such re-bar configuration is not effective in resisting bidirectional lateral load; In order to maximize the bidirectional lateral load resistance (flexural capacity), it is advantageous to concentrate steel area on the corners of the core wall-cross section.
2) In high-rise buildings, outriggers, which connects core wall to perimeter columns, are frequently used to enhance the lateral load resistance. In the outrigger-installed floors, to transmit significant force, the corners of the core wall are strengthened with vertical and horizontal steel members. Further, for their interferences with wall construction, auto climbing system (ACS) forms need to be removed, and reinstalled. Thus, the construction cost and time are significantly increased: about 2~3 months per outrigger-installed floor.

In the present study, to improve the structural capacity and economy, a novel composite core wall system using steel plate columns at the corners of the core wall section was developed.

2. Corner steel plate reinforced wall method

Figure 1 shows the conceptual design of a corner steel plate-reinforced core (CSRC) wall. In the method, twin angle-shaped steel plate columns are placed at the four corners of the core wall cross section. To provide connectivity to steel beams and outriggers and lateral confinement to the concrete wall, the steel plate columns are placed at the surface of concrete walls. By using such configuration of steel, the following advantages are expected. (It should be noted that the corner steel area is designed by rearranging the uniformly distributed rebar area rather than using additional steel area at the corners). 1) The flexural strength and stiffness of the wall can be increased. In the case of super-high rise buildings, the lateral load resisting system is determined to control the lateral displacement. In this case, lateral stiffness is important. Considering the large elastic modulus of the steel, which is 7~8 times that of high strength concrete, the stiffness of the core wall can be significantly increased by the steel columns located at the corners of the wall; 2) The required amount of re-bars can be reduced by replacing the majority of re-bars with steel plates. Thus, labor cost and construction time related to re-bar work can be reduced; 3) The wall thickness can be reduced, which can increase available floor area; 4) The corner-steel plate columns can provide high stiffness and connectivity to support outriggers.

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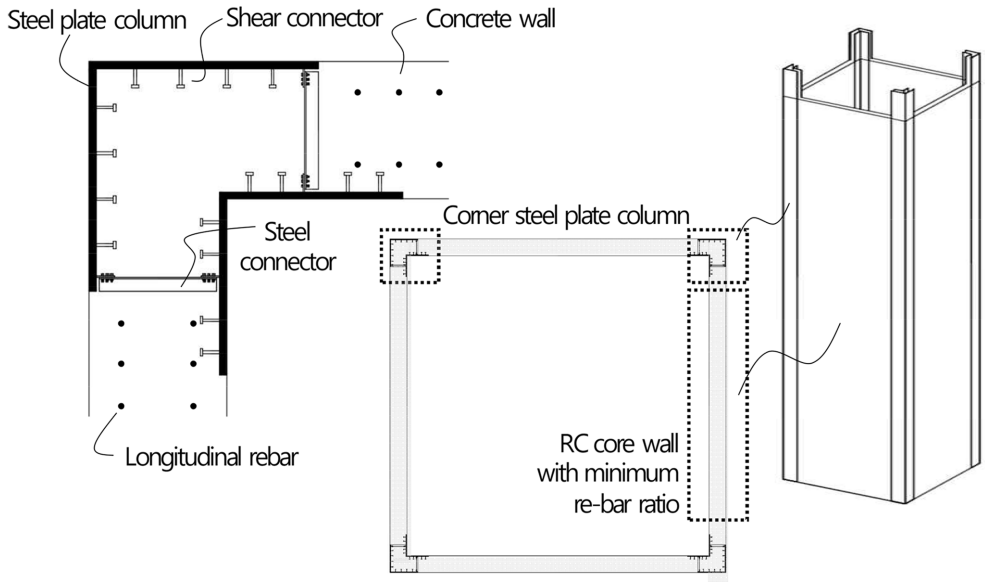


Figure 1. Proposed corner steel plate reinforced core wall method.

Thus, additional strengthening steel members can be reduced or unnecessary; 5) Usually, large openings are located in the core walls, which degrade the structural capacity of the wall. The corner steel plate columns can provide additional resistance to the core wall (Usually, openings are not located at the corners); and 6) The steel plate column can increase the shear strength of the wall. Thus, the shear resisting bars in the wall can be reduced.

3. Sectional structural capacity

To investigate the effect of the corner-steel plate wall on the structural capacity of the core wall, nonlinear section analysis was performed using strain-compatibility method (should be replaced by ACI 318-19 and KBC 2016). Figure 2 shows geometric configuration of the prototype core wall section. The dimensions of the core section were 30×30 m, and the wall thickness was 1,000 mm. For simplicity, the openings and interior walls were neglected. For conventional RC core wall (RC-core), the total area ratio of longitudinal re-bars to the gross section (= re-bar ratio) was defined as ρ_r =2.0%. For CSRC wall, eight L-section steel plate columns (equal legs) of L-2650×50mm (leg width×thickness) (CSRC-1A, -1B, and -1C) or L-2650×80 mm (CSRC-2A, -2B, and -2C) were used at the exterior and interior corners of the core wall section. The strengths of concrete, steel, and re-bar used for the section analysis were 50~80MPa, 650MPa, and 600MPa, respectively. From the section analysis of CSRC walls, the minimum values of the wall thickness, re-bar ratio, and concrete strength required to satisfy the structural capacity of RC-core wall were investigated.

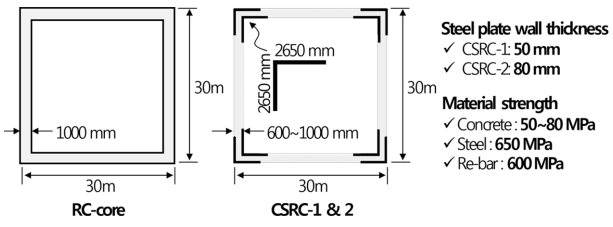


Figure 2. Prototypes of RC core wall and CSRC wall.

3.1.Effect of steel ratio

In this study, the wall thickness was maintained as 1000 mm. In CSRC-1A and CSRC-2A, the rebar ratio was ρ_r = 0.2%, which was 90% less than that of RC-core. The area ratio of the steel plate column was ρ_s = 1.8% for CSRC-1A and ρ_s = 2.9% for CSRC-2A, respectively. Thus, the overall steel ratio ($\rho_s + \rho_r$) of CSRC-1A is the same as that of RC-core and the overall steel ratio of CSRC-2A is increased by 1.1%. Figure 3 shows the P-M interaction relationship and flexural stiffness of RC-core and CSRC-1A and -2A sections. The flexural stiffness of the composite section (non-cracked wall for elastic analysis, according to ACI 318 and KBC 2106) was defined as $EI = 0.7E_cI_c + E_sI_s + E_{sr}I_r$ (ACI 318 and KBC 2016), in which E_c, E_s, and E_{sr} = elastic modulus of concrete, steel, and re-bar, respectively; I_c, I_s, and I_r = second-order moments of inertia (with respect to the centroid of the core section) of concrete, steel, and re-bar, respectively.

In the case of CSRC-1A (ρ_s = 1.8%, ρ_r = 0.2%), despite the same steel ratio, the maximum flexural capacity (denoted as a circled mark in Figure 3) was increased by 9%, under 0.3 axial force ratio. The flexural stiffness was increased by 6%. For the re-bars and steel columns, the flexural stiffness contribution ($E_sI_s+E_{sr}I_r$) was 36% greater than that of re-bars in RC-core ($E_{sr}I_r$). In CSRC-2A (ρ_s = 2.9%, ρ_r = 0.2%), by increasing the steel plate thickness, the maximum flexural capacity and flexural stiffness were

Table 1. Section analysis parameters

Specimens	Concrete strength (MPa)	Wall thickness (mm)	Steel ratio, % (steel section)		
			Re-bar	Steel plate column	Total
RC-core	80	1000	2.03 (D35@140)	0	2.03
CSRC-1A	80	1000	0.21 (D19@275)	1.81 (L-2650×50)	2.02
CSRC-2A	80	1000	0.21 (D19@275)	2.88 (L-2650×80)	3.09
CSRC-1B	80	930	0.22 (D19@275)	1.94 (L-2650×50)	2.16
CSRC-2B	80	800	0.26 (D19@275)	3.58 (L-2650×80)	3.84
CSRC-1C	70	1000	0.21 (D19@275)	1.81 (L-2650×50)	2.02
CSRC-2C	50	1000	0.21 (D19@275)	2.88 (L-2650×80)	3.09

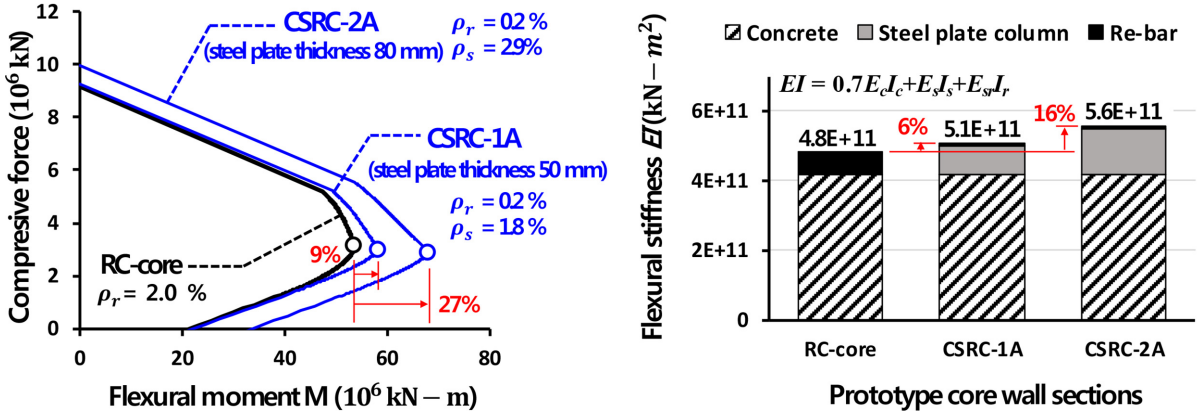


Figure 3. Effect of steel ratio on structural capacity of core wall.

27% and 16% greater than those of RC-core, respectively.

3.2. Effect of wall thickness

Figure 4 shows the P-M interaction relationship and flexural stiffness of RC-core and CSRC-1B, 2B sections. CSRC-1B and CSRC-2B have the same amount of re-bars as that of CSRC-1A and CSRC-2A (Because of the smaller wall thickness, the re-bar ratio was increased in Table 1). In the case of CSRC-1B, despite less wall thickness (930 mm, 7% less), the flexural stiffness was comparable to that of RC-core, and the maximum flexural capacity was 7% increased. In the case of CSRC-2B using larger steel plate columns, the wall thickness can be further reduced. For the same flexural stiffness as that of RC-core, the wall thickness can be decreased to 800 mm (20% less), which allows greater floor area. In this case, the maximum flexural capacity was 16% increased.

3.3. Effect of concrete strength

Figure 5 shows the P-M interaction relationship and flexural stiffness of RC-core and CSRC-1C, 2C sections. In CSRC-1C and CSRC-2C, the steel configuration and wall thickness are the same as those of CSRC-1A and CSRC-2A, respectively. In the case of CSRC-1C, despite the lower concrete strength (70MPa, 13% less), the maximum flexural capacity and flexural stiffness were

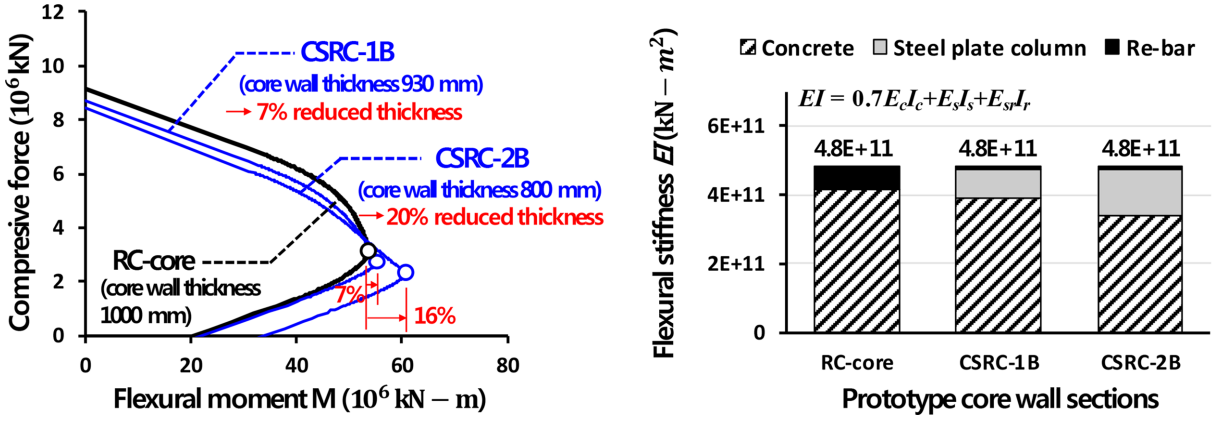


Figure 4. Effect of wall thickness on structural capacity of core wall.

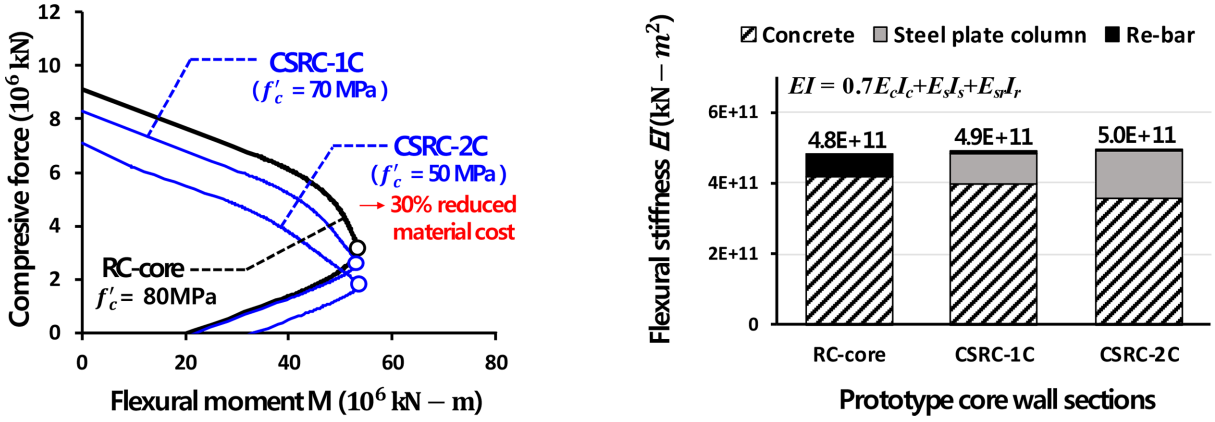


Figure 5. Effect of concrete strength on structural capacity of core wall.

Table 2. Material cost estimation for section analysis

Sections	Area (m^2)			Material cost ($) for unit height of core				Cost ratio (CSRC/RC)
	Concrete	Re-bar	Steel	Concrete	Re-bar	Steel	Total	
RC-core	114 (80MPa)	2.4	0	17,047	2,355	0	19,402	-
CSRC-1A	114 (80MPa)	0.2	2.1	17,049	244	3,149	20,442	1.05
CSRC-2A	112 (80MPa)	0.2	3.3	16,862	244	5,011	22,117	1.14
CSRC-1B	106 (80MPa)	0.2	2.1	15,871	238	3,147	19,255	0.99
CSRC-2B	90 (80MPa)	0.2	3.3	13,478	243	5,018	18,738	0.97
CSRC-1C	114 (70MPa)	0.2	2.1	17,049	244	3,149	20,442	1.05
CSRC-2C	112 (50MPa)	0.2	3.3	11,242	244	5,011	16,496	0.85

Note: Unit price of concrete = 150$/m3 (70~80MPa) and 100$/m3 (50MPa); steel = 1500$/ton; re-bar = 1000$/ton.

comparable to those of RC-core. In CSRC-2C, the concrete strength can be further decreased to 50MPa (38% less). Due to the greater flexural contribution provided by larger steel plate columns, the maximum flexural capacity and flexural stiffness were slightly increased.

3.4. Material cost

For RC-core, CSRC-1 and -2 sections, the corresponding material cost including concrete, steel, and re-bars (for unit height of core) was calculated from Table 2 and Table 3. In the case of CSRC-1A, -2A, and -1C, due to the higher price of steel (1000$/ton for re-bar, 1500$/ton for steel), the material cost (20,442~22,117$) was 5~14% higher than that of RC-core (19,402$). In CSRC-1B and -2B with less wall thickness, the material cost (19,255$ and 18,738$) was slightly decreased, despite the use of corner-steel plate columns. In the case of CSRC-2C, using 50 MPa-concrete (100$/$m^3$ which is about 30% less than that of 80 MPa-concrete (150$/$m^3$), based on construction material costs in Korea), the material cost (16,496$) can be reduced by 15%.

4. Case study for 120-story prototype building

To verify the system level-structural performance, the corner steel plate composite core wall was applied to a design of 120-story buildings. Figure 6 shows the structural system of the building using a mega column system. The structural system consists of a RC core wall, RC mega-columns, and steel outrigger brace. The corresponding sections and material strengths are shown in Figure 6. The load combination of dead loads (including slab weight), wind loads, and live loads was defined according to ASCE 7-10. The dimensions of the floor plan and core wall are 60 × 60m and 30 × 30m, respectively. The building has 120 floors, and the floor height is 4.5m. The outriggers are placed at 39-43F, 72-76F, and 103-107F. The core wall-thickness ranges from 600mm to 1600mm. The roof lateral drift ratio was 1/500. In the application of corner-steel plate columns, considering the lifting capacity of tower cranes, the unit weight of the steel plate (9 m-height corresponding to 2 floors) was limited to 60,000kg. Thus, the width and thickness of the steel plates ranged 2500~4500 mm and 80~120 mm, respectively. The concrete strengths of the core wall and mega-columns were 70 to 80MPa. Using MIDAS-GEN program, 3-dimensional elastic structural analysis was performed, and the variation of roof displacement according to the corner-steel plate columns was evaluated.

4.1. Effect of application height of corner-steel plate

The application height of corner-steel plate columns was increased from ground to every 10 stories: 1-10F, 1-

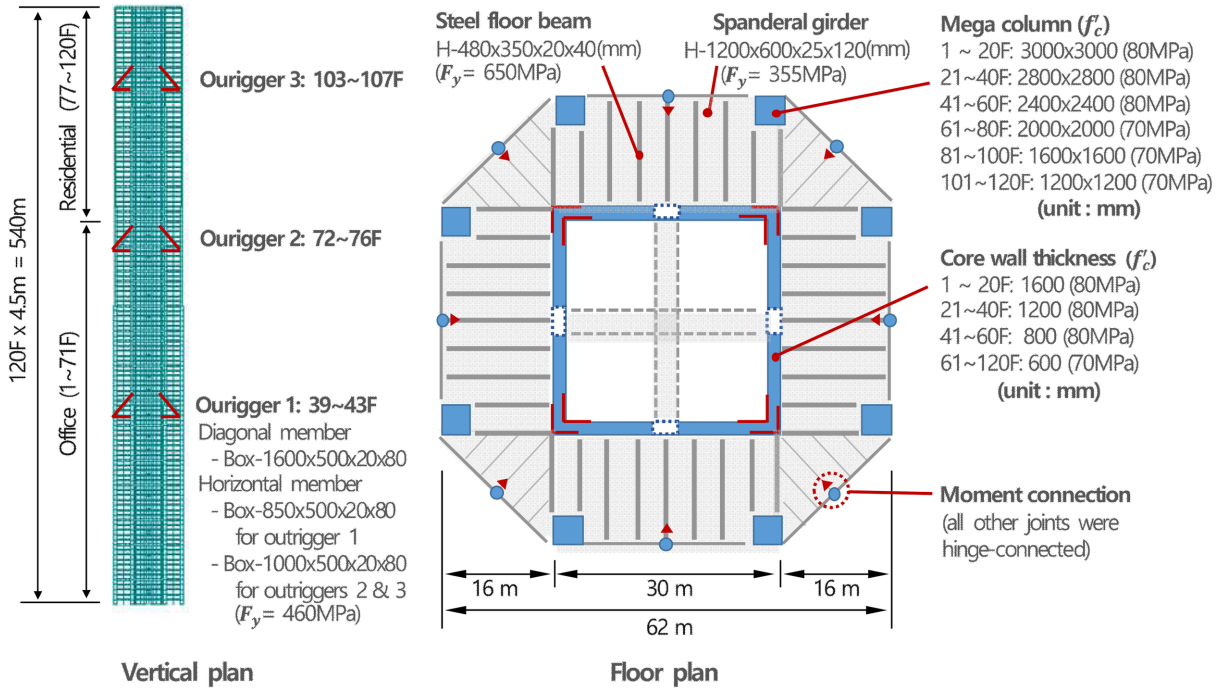


Figure 6. Structural system of 120-story building using RC core wall.

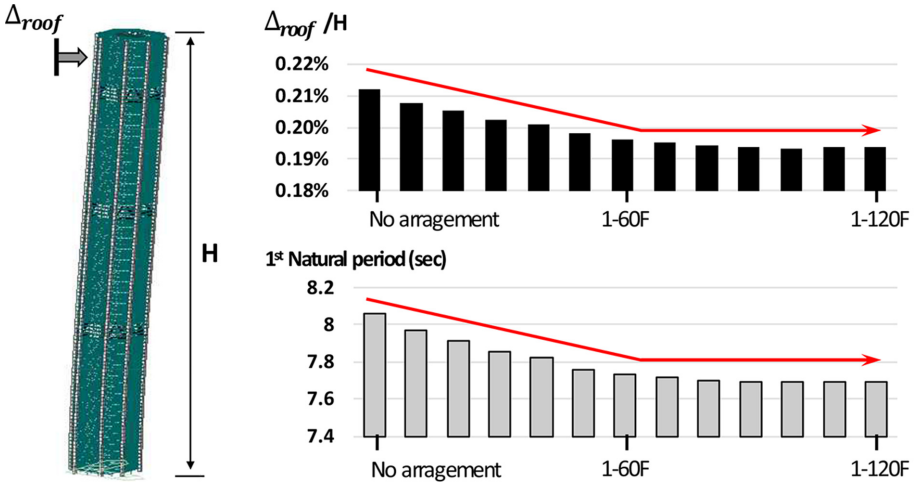


Figure 7. Effect of application height of corner-steel plate columns.

20F, etc. For the steel column, L-2500 × 80 section was used. The effect of the application height is shown in Figure 7. Until the application to 60th floor, the roof displacement (Δ_{roof}) and 1st-order natural period were linearly decreased (the lateral stiffness increased) as the application height of the steel columns increased. However, beyond 60 stories, the lateral stiffness did not significantly increase. Thus, for efficient use of the steel columns, it is recommended to use corner-steel plate columns below half of the building height (H).

4.2. Effect of core wall thickness

By placing the corner-steel plate columns, core wall thickness can be reduced, which enhances the economy and constructability of the building. In this study, the construction cost and time were evaluated as shown in Table 3. For cost estimations, additional steel cost, concrete/re-bar saving, and sale revenue of floor space were considered. For construction time estimations, corner steel plate connection, concrete casting, formwork (for concrete), and re-bar work were considered. The lateral displacement was maintained to be the same as that of the RC core wall case.

Figure 8 shows the core wall thickness variation, lateral displacement, cost saving, and reduced construction time of three different core wall designs, respectively. When corner-steel plate columns of L-2500 80 were used for 1~40F (Case 1), the core wall thickness can be reduced to

Table 3. Construction cost and time for case study

Cost	Construction time
Material Cost - Steel: 1,500 $/ton - Concrete: 150 $/m3 (for 80 MPa) - Re-bar: 1,000 $/ton Sale revenue per floor area (office of high-rise buildings in Seoul) - 16,700 $/$m^2$	Time increasing - Corner steel plate lifting/connecting : 1 hour/steel plate unit (bolt work) Time decreasing - Concrete casting: 30 m^3/hour - Concrete form: 2 m^2/hour (for 20 workers) - Re-bar work: 500 sec/each (for 20 workers)

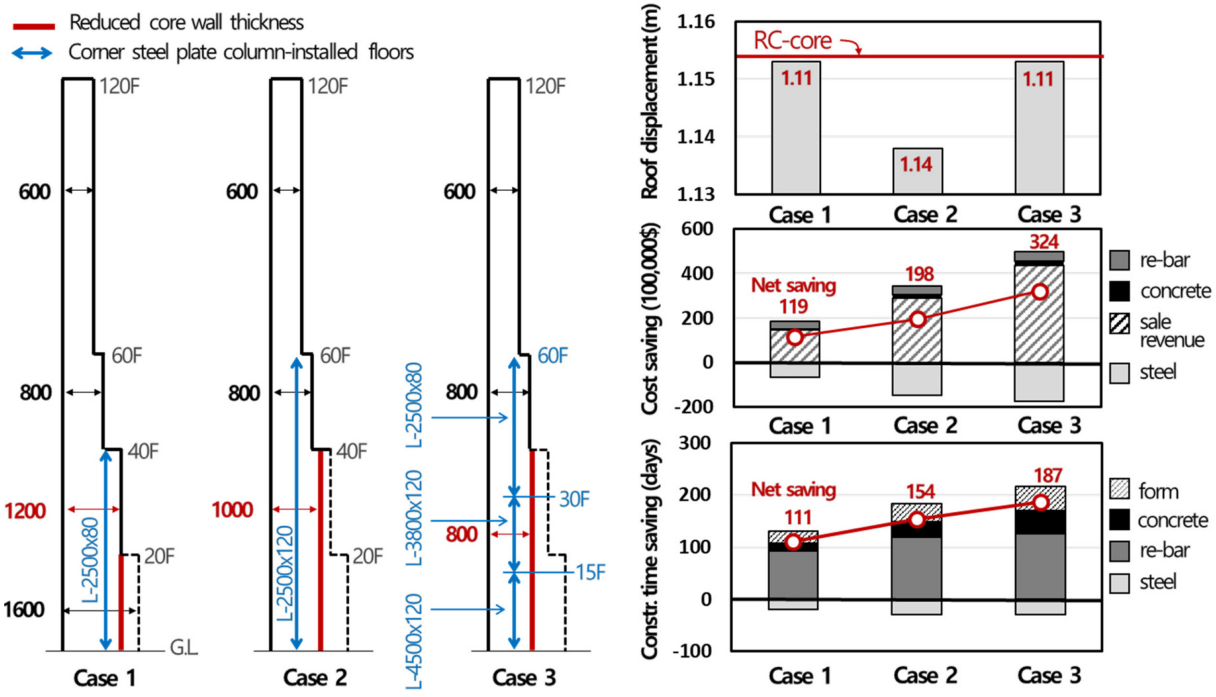


Figure 8. Effect of wall thickness on structural capacity and construction economy.

1200mm for 1~20F. Thus, the floor area is increased by 48m2 (= 4 0.4m 30m) for 1~20F. On the basis of cost estimation in Table 3, the cost saving is 11,900,000$, and the construction time can be reduced by 111 days. When L-2500 120 is used for 1~60F (Case 2), the core wall thickness can be reduced to 1000mm for 1~40F. In this case, the cost saving and reduced construction time are 19,800,000$ and 154 days, respectively, which are 66% and 39% greater than those of Case 1. When corner steel plate columns of L-4500 120 at 1~15F; L-3800 120 at 16~30F; and L-2500 80 at 31~60F were used (Case 3), the wall thickness can be reduced to 800mm for 1~60F. In this case, the cost saving and reduced construction time are increased to 32,400,000$ and 187 days, respectively. Further, by using the uniform core wall thickness for 60 stories, the ACS form cost can be reduced.

5. Conclusions

In the present study, a novel composite core wall system using corner steel plate columns was studied for efficient structural performance and construction economy of high-rise Building. By performing section analysis and structure analysis, the effect of the corner steel plate columns was investigated. The result is summarized as follows:

1) The result of section analysis for core wall showed that, for the same flexural stiffness as that of RC-core, the use of the corner steel plate columns (using the same amount of steel in RC-core) can lead to 7% reduction of the core wall thickness.
2) By using the corner steel plate columns (steel ratio is 1.1% higher than that of RC-core), the available concrete strength can be reduced from 80 MPa to 50 MPa (for the same amount of concrete as that of RC-core), which allows cost saving of the concrete. In this case, the material cost including concrete, steel, and re-bars can be reduced by 15%, despite the use of corner steel plate columns.
3) In the case study of 120-story buildings, corner-steel plate columns can be efficiently used to half of the building height. When the steel columns L-2500 × 120 are used for 1~60F (= 0.5H), the wall thickness

can be reduced from 1600~1200mm to 1000 mm. The corresponding cost-saving and construction time-saving were estimated as 19,800,000$ and 154 days, respectively.

4) When corner steel plate columns of L-4500 × 120 at 1~15F; L-380 × 0120 at 16~30F; and L-25 × 0080 at 31~60F are used, the core wall thickness can be reduced to 800mm. The corresponding cost saving and construction time-saving were estimated as 32,400,000$ and 187 days, respectively.

In the case study of 120-story buildings, due to the high lateral load resistance of the outrigger system, the replacement of the outriggers by the steel plate columns was not considered. However, in the case of relatively smaller high-rise buildings (50-80 stories), the lateral load resistance of the core wall can be further increased by using the steel plate columns, so that the use of the outriggers can be reduced or unnecessary. For verification of structural performance, experimental studies for steel plate-concrete bond strength, flexural/shear resistance of corner steel plates, and applicability of current design methods are required.

6. Acknewledgements

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