Development of auto-climbing formwork system for composite core walls

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ABSTRACT

This study was conducted to develop a corner-supported auto-climbing formwork system (CS-ACS) that uses steel plates installed at the corners as support points in connection with the development of a steel-concrete composite core-wall structural system. For the optimal design of the CS-ACS, a numerical study using FE approach was conducted on the concrete lateral pressure acting on the form during construction and the wind load that may occur when the formwork is lifted. Through the foregoing, each constituent member of the system was optimally designed and displacement and stress calculation equations that can be used for design were proposed. For the lateral pressure of concrete, an analytical study was conducted with about 400 variables, and for the effect of wind load, a study was conducted with 50 variables so that the members can be optimally designed. Through the study, it was found that the CS-ACS is more advantageous than the existing cantilever type ACS for structural stability, displacement, and stress control because it can form a formwork system as a simply supported flexural member using the preinstalled end steel plates as support points and can reduce the burden of lifting as the unit weight of the system can be designed at a level that is half of that of the existing ACS.

1. Introduction

1.1. Background and purpose

Formwork development has paralleled the growth of concrete construction throughout the twentieth century (Hanna 1999). With advancements in high-rise building construction, the need for safe and efficient vertical formwork systems has arisen. Therefore, special attention is placed on the design and development of auto-climbing vertical formwork systems to increase the efficiency of high-rise building construction (Zayed et al., 2008).

Typical vertical formwork systems include conventional formworks, ganged forms, jump forms, slip forms, and automatic climbing forms (Sharifi, Baciu, and Zayed 2006). These systems can be classified into two main categories, namely, crane-dependent systems and crane-independent systems. Gang and jump forms are classified under crane-dependent systems. Slip and automatic climbing forms are classified as crane-independent systems in which formwork panels are moved vertically with the help of jacks that are operated hydraulically, electrically, or pneumatically (Hanna 1999).

The Auto-Climbing formwork System (ACS) is a method of construction in which the formwork is combined with a set of equipment such as hydraulic cylinders and guide profiles so that the system is supported by using anchor bolts on the lower story concrete wall, as shown in Figure 1, without being supported by a tower crane, and the system is automatically lifted along guide rails using a hydraulic jack. The ACS has been widely used around the world for bridge piers and high-rise reinforced concrete buildings. (Yang et al., 2012)

The ACS has the advantages of high construction speed and excellent quality, but has disadvantages that its safety is greatly affected by the construction quality of the concrete because its support points are formed on the concrete wall constructed below, and that the process is interrupted during the curing period of the concrete. In addition, there have been cases where the system crashed because the anchor bolts were removed due to the poor quality of the precasting lower story concrete (KOSHA committee, 2010).

In particular, the ACS used for high-rise buildings is affected more by wind loads at higher floors. Therefore, recent studies on safety control during their operation (Liu et al. 2012) and studies on the consideration of the formwork vibration reaction caused by wind when working at high altitudes in traditional ACS (Hu and Li 2019) have analyzed the relevant effects.

In addition, in high-rise buildings, outriggers that connect the core wall with the surrounding columns are installed to increase the resistance to lateral loads, and the edges of the core wall are reinforced with...
vertical and horizontal steel members to transmit force from the floor where the outriggers are installed. In this case, situations where the ACS should be removed and reinstalled occur because the ACS interferes with wall construction. This increases the construction time by about 2–3 months and costs per floor where the outriggers are installed (Park et al., 2019).

Therefore, in order to improve the structural capability and economic efficiency, a steel-concrete composite core-wall structural system using steel plate columns at both ends of the core was developed (Hong and Shim, 2019) (Figure 2).

This study aimed to develop a formwork system with improved safety and constructability applicable to steel-concrete composite core-wall construction by supplementing the shortcomings of the existing ACS in connection with the development of the steel-concrete composite core wall.

![Figure 2. Steel-concrete composite core wall.](image)

### 1.2. Content of the study

A Corner-Supported Auto-Climbing Formwork System (CS-ACS) was developed in which the support points for lifting the ACS were changed from the lower story concrete wall that had been used in the existing system to high-strength, high-stiffness corner steel plate walls installed at both corners of the steel-concrete composite core-wall structural system to improve construction safety, which can simplify processes and shorten the construction period as the number of support points was reduced. In order to apply the CS_ACS, it has a limitation that the composite core wall should be used as the core structural system. However, it is expected that it can be applied to the core of steel structures in the future.

In this study, for the optimal design of the developed formwork system, the safety of the CS-ACS against concrete lateral pressure and wind loads was evaluated in comparison with the existing ACS through FEM analysis. Structural analysis for concrete lateral pressure was conducted using MIDAS-GEN program optimized for member design of building structures, and ABAQUS, a finite element analysis program, was used to examine the stress distribution and displacement within the element for stability against the wind load.

### 2. System development

#### 2.1. Concept of the CS-ACS

Whereas the existing ACS is greatly affected by wall curing conditions, concrete strength, and the skill of the workers who fasten the anchor bolts, because the support points for the formwork system are formed on the lower story concrete wall by embedding anchor bolts in the wall to support the formwork system in the form of cantilevers, in the case of the corner-supported auto-climbing formwork system (CS-ACS) designed in this study, support points are formed on the high-strength/high-stiffness steel plate walls installed on the corners at both ends in connection with the steel-concrete composite core-wall structural system, as shown in Figure 3, so that the system is supported by the corner steel plate walls at both ends to improve construction stability and stability against wind loads. The processes can be simplified and the construction period can be shortened because the support points are reduced compared to when the formwork system is supported by the lower story concrete wall. According to the analysis of field engineers, CS-ACS can reduce the construction period approximately by 0.5 days per floor in summer and 1 day in winter.

#### 2.2. Composition of members

The constituent members of the CS-ACS formwork consist of horizontal members connecting the support
3. Optimal design of constituent members

3.1. Concrete pressure during construction

3.1.1. Method
In this study, the lateral pressure of concrete acting on the formwork during construction was considered to derive the optimal sectional performance to respond to the lateral pressure, and at the same time, the optimal design was conducted to improve the constructability and reduce the load on the lifting system by minimizing the weight of the system.

Midas-Gen, a commercial structural analysis program, was used for the analysis of the formwork system, and the sectional performance of the horizontal member (moment of inertia), the spacing of the horizontal members, the spacing of the form ties, and the height and span of the formwork system were set as variables to carry out analyses of about 400 variables. The required sectional performance and installation spacing that satisfy the level of displacement and stress of the formwork frame that can secure the safety required by the design code were derived and the system was designed based on the resultant sectional performance and installation spacing.

3.1.2. Design variables and analysis method
In this study, as shown in Figure 6, a case where 2.5-m-long steel plate walls are installed at the corners of a 24-m-long steel composite core wall was assumed and a 20 m long and 3 m high formwork frame was set as a basic module to assume that the core wall would be constructed on the frame. The analysis was carried out while adjusting the design variables.

The material performances of the members used for the analysis are as shown in Table 1. The analysis variables are (1) sectional performance of horizontal members, (2) installation spacing of horizontal

Figure 6. General composition of CS-ACS.
members, (3) installation spacing of form ties, (4) formwork frame span, and (5) formwork frame height, and the details are shown in Table 2.

The concrete lateral pressure (P) acting on the formwork was calculated as shown in Equation (1) according to the Korean formwork design code, the unit weight of reinforced concrete (W) was set to 24 kN/m³, and the placement height was set to 3 m ~ 5 m, which was the value corresponding to the height of the formwork (ACI committee 347, 2004; KTEA committee, 2016). In addition, the shape of the lateral pressure was assumed to be triangular-shaped uniformly varying loads that increase toward the bottom and was implemented using hydrostatic pressure in the analysis program.

\[ P = W^*H \quad (\text{kN/m}^3) \]  

- P: Concrete lateral pressure (kN/m³)  
- W: Unit weight of fresh concrete (kN/m³)  
- H: Concrete placement height (m)

Resistance to concrete lateral pressure is supported by the sheathing board followed by the horizontal members and finally by the form ties that tie the horizontal members.

In the analysis, a boundary condition that constrains displacement in all directions to the opposite node of the beam element corresponding to the form tie was created to implement the form of support for the lateral pressure (Figure 7). In cases where the stress of the form tie exceeded the yield stress, the installation of additional form ties was allowed, and the cross-sectional area of the form ties was also increased by two or three times when the analysis was conducted. The connection between the form tie and the horizontal member was assumed to be a pin connection, and the beam and release function provided by the analysis program was used. Since the cross section of the formwork member is symmetrical, only half was modeled around the center of Figure 7 and the concrete lateral pressure was applied to the surface of the formwork, and the form tie penetrating the cross section was modeled up to the opposite side.

### 3.1.3. Analysis results and analysis

Through the analysis of each variable, the displacement and stress of the formwork frame were identified and compared with the form deformation limit presented in the design code. The deformation limit stipulates that the displacement and stress of the formwork frame should be classified according to the classes of the surface and that the displacement should not exceed the smaller of the relative deformation and absolute deformation according to the form tie space. Table 3 shows the absolute and relative deformations by surface class. As shown in Figure 8, the deformation and stress of the formwork behaved in the form of a continuous beam due to the form ties installed at regular distances so that the maximum displacement of the horizontal member and the maximum stress of the form tie appeared at the lower end of the frame. In addition, as the form tie space increases from 1,000 mm to 2,000 mm, the maximum stress and maximum displacement of the form tied increase from 185 MPa to 389 MPa and from 0.446 mm to 1.724 mm, respectively, indicating that the effect of form ties is the largest on the control of formwork displacements.

In addition, the sectional performance of the horizontal members and the formwork spans were adjusted stepwise to 1.0 × 10⁻⁴ ~ 10.0 × 10⁻⁴ mm² and 20 ~ 50 m, respectively, when the effects were analyzed, but the effects on the displacement of the formwork frame and the form tie stress were found to be insignificant. It is assumed that as the form tie resisted the displacement of the formwork due to the lateral pressure of the concrete by playing the role of a point, the sectional performance of the horizontal members and the formwork spans had little effect. Therefore, it can be seen that the displacement of CS-ACS in which both ends of the core are support points due to the lateral pressure of concrete can be controlled with form ties installed at regular distances. However, it was found that the height of the formwork frame proportionally increases the load applied to the system, thereby directly affecting changes in the displacement of the formwork and the form tie stress. Accordingly, as shown in Figure 9, it can be seen that when the height of the formwork frame is 3 m, the stress of the form tie is less than 200 MPa regardless of the type of horizontal member, which means that the safety factor is quite high, and that the stress acting on the form tie is close to the yield strength. In addition, it was shown that as the spacing of the form ties increases, the stress of the form tie and the displacement of the frame

| Table 1. Constituent member properties for analysis. |
|-----------------------------------------------|
| Modules of elasticity | Material | Basic section |
| Form tie | SD400 | 11 × 10⁴ | D16, Round Shape |
| Sheathing board | 15 T | 200 × 10⁴ | - |
| Vertical member | SS275 | 210 × 10⁴ | C-150 × 75 × 65/ |
| Horizontal member | SS275 | 210 × 10⁴ | H-150 × 150 × 7/ |

| Table 2. Variables of concrete pressure analysis research. |
|-----------------------------------------------|
| Moment of inertia of horizontal member | Distance of horizontal member | Form tie space | Formwork frame span | Formwork frame height |
|-----------------------------------------------|
| 1.0 × 10⁻⁴ | 500mm | 500mm | 20m30m | 3m |
| 10.0 × 10⁻⁴ | 750mm | 1,000mm | 40m | 3.5m |
| mm² | 1,000mm | 1,500mm | 50m | 4m |
| | 1,250mm | 2,000mm | 4.5m | |
| | 1,500mm | | 5m | |
are affected more by the height of the formwork. When the form tie spacing is 1,500 mm or more and the formwork height is 3.5 m or more, the form tie stress reached about 350 ~ 370 MPa. Therefore, 1,000 mm was determined to be the optimum spacing of the form ties and fixed, because at that spacing, the form tie stress was not higher than 300 MPa at all formwork heights and the number of form ties installed was thought to be appropriate.

In order to predict the displacement of the formwork frame and the stress of form ties, which vary according to the height of the formwork and the spacing of the form ties, a regression analysis was conducted that synthesized the analysis results, and the following model equations (Equations 2 and 3) were proposed. It can be seen that the values calculated by the proposed equations predict the analysis results very accurately, as shown in Figure 10.

\[
\delta_{\text{form}} = ah + \gamma_1
\]  

(2)
• $\delta_{\text{form}}$: Max. displacement of the formwork frame (mm)
  $\alpha: 0.114d^2 + 0.06d + 0.06$
  $\gamma_1: -0.08d^2 + 0.05d - 0.04$
  $$\sigma_{\text{form-tie}} = \beta h + \gamma_2$$ (3)

• $\gamma_2: -21d^2 + 22d - 22$

where, $h$: Formwork frame height (m),
$d$: form tie space (MPa)

The spacing of the horizontal members has a great effect on the total weight of the formwork frame. Therefore, in order to derive the optimal spacing of the horizontal members that can reduce the total weight of the frame while securing structural safety, 1,000 mm, which is the optimal spacing of the form ties determined through the analysis mentioned above, was set as a fixed variable and the distribution of horizontal member layers that can appear when the height of the formwork is set at 3 ~ 5 m is shown in Figure 11. The horizontal member layers were arranged at equal distances in principle, but in cases where they could not be, they were arranged at equal distances for as long as possible and the space of the top layer was increased. In addition, 400 MPa steel bars were used as the form ties, but considering safety, 300 MPa was assumed as the allowable stress, and when the stress generated in a form tie exceeded 300 MPa, two form ties were installed. The layers in which additional form ties should be installed are shown in Table 4.

Since the composition of the workspace, etc. excluding the formwork frame of the existing ACS is identical to that of the CS-ACS, only the weights of the formwork frame itself were analyzed, and the results are as shown in Figure 12. According to the analysis, in the case of the CS-ACS, the weight of the frame changes dramatically according to the spacing of horizontal members. When the spacing of the horizontal members was 500 mm, the unit weight was about 75 ~ 80 kg/m², and when the spacing was 750 mm or more, the rate of change of the weight was reduced, and the unit weight at a spacing of 1,000 mm was shown to generally be 40 ~ 50 kg/m², indicating that the CS-ACS can be made to be lighter compared to the existing ACS, the unit weight of which is generally about 100 kg/m².

3.2. Wind load during lifting

As shown in the results of the analytical study of the lateral pressure of concrete, the displacement and stress of the formwork system due to lateral pressure are mainly determined by the form ties that anchor the formwork, and the horizontal members constituting the system came to have large effects on the total weight of the formwork rather than the structural aspect. However, another item that must be considered when designing the formwork system is the effect of the wind load that may occur during formwork lifting. When the formwork is lifted, since the inner and outer formworks cannot be anchored, and the formwork is independently lifted after it is separated from the walls, only the formwork frame must resist the wind load applied during lifting. Whereas the existing ACS resists the wind load in the form of a cantilever because the support points are below the ACS, the CS-ACS is structurally advantageous because it is supported at both ends and can be lifted along the guide rails pre-installed on the upper part while the upper and lower parts are fixed together. A finite element analysis using ABAQUS was conducted to evaluate the structural performance against the

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**Figure 11.** Example of formwork frame layer.

**Table 4.** Additional form tie installation layer of formwork frame.

| Layer Distance | 3 m x 20 m | 4 m x 20 m | 5 m x 20 m |
|----------------|------------|------------|------------|
| Additional form tie layers | Additional form tie layers | Additional form tie layers |
| 500 mm | - | - | - |
| 750 mm | - | - | Two layers |
| 1,000 mm | Two layers | Two to three layers |
| 1,250 mm | Two layers | One to three layers |
| 1,500 mm | One to two layers | One to three layers |
wind load during lifting. The standard wind velocity of 35 m/s was applied as the wind load according to the provisions of the KBC Committee 2016. Since 35 m/s is the design wind load of the completed building, 30 m/s that the load conditions at the time of construction were taken into account was also analyzed by referring to the construction conditions of existing ACS.

The design velocity pressure qH was calculated according to the KBC code as shown in Figure 13. As shown in Figure 14, the model for analysis used the C3D8R element as a three-dimensional element that follows the three-dimensional stress–strain relationship, and the thickness direction was quartered when modeling the element in order to accurately consider the out-of-plane bending behavior. The wind load was input as a pressure load acting uniformly on the form face, and load control was conducted. As shown in Figure 15, displacement was measured by measuring the loading direction displacement at the upper center of the formwork and the edge of the steel plate wall where the greatest displacement occurred.

The model used in the analysis used the existing ACS as a control specimen and analyzed a total of 50 variables, including 24 types of CS-ACSs and two types of wind velocities as presented in Table 5.

On reviewing the major results of the analysis for wind loads, it could be seen that, as shown in Figure 16, when the spacing of horizontal members was set to 1 m, the maximum displacements of all forms were superior to those of the existing ACS, and when a member of 150*150*7/10 with the minimum cross section was used, displacement about 85% of that of the existing ACS occurred, and when a member of 300*300*10/16 with the maximum cross section was used, the displacement could be reduced to 62%. In addition, as shown in Figure 17, it can be seen that the maximum stress generated in the member was about half of that of the existing ACS.

On reviewing the tendency of the displacements according to the spacing of the horizontal members, it could be seen that, as shown in Figure 18, the larger the spacing of the horizontal members, the more constantly the displacement increased, but the displacement control performance was still superior to that of the existing ACS. When the span of the formwork system was increased to 30 m, the amount of displacement of the formwork increased significantly, as shown in Figure 19, but it was about 0.03 ~ 0.04% of the span length at a wind speed of 35 m/s, and the displacement occurring in the steel plate at the end support point was still not big.

4. Summary and conclusions

The following conclusions can be drawn from the results of the numerical study of CS-ACS, a modified formwork system that uses the corner steel plate of a steel-concrete composite core-wall structural system.

(1) Since the CS-ACS uses pre-installed end steel plates as support points to form the formwork system as a simply supported flexural member, better structural stability than the existing ACS can be secured and the construction period can be shortened regardless of the curing of the lower story concrete.

(2) According to the analysis, the displacement of the formwork due to the lateral pressure of concrete can be controlled by form ties, and there are little effects of other constituent members such as horizontal and vertical members.
Figure 15. General deformed shape of formwork.

Table 5. Analysis variables and results summary at wind velocity 35 m/s.

| Sortation | Horizontal member | Member space (mm) | Description | Maximum displacement (mm) | Maximum stress (MPa) |
|-----------|-------------------|------------------|-------------|----------------------------|----------------------|
| DA-1      | 150*150*7/10     | 500              | Form corner steel | 7.51 | 1.32 | 3.8 | 3.12 |
| DA-2      | 175              | 1000             | Form corner steel | 8.38 | 1.35 | 4.01 | 3.46 |
| DA-3      | 200*200*8/12     | 500              | Form corner steel | 8.93 | 1.37 | 3.76 | 3.58 |
| DA-4      | 225              | 1500             | Form corner steel | 9.53 | 1.39 | 4.98 | 3.59 |
| DA-5      | 250*250*9/14     | 500              | Form corner steel | 5.95 | 1.27 | 3.43 | 3.06 |
| DA-6      | 275              | 750              | Form corner steel | 6.94 | 1.33 | 3.55 | 3.43 |
| DA-7      | 300*300*10/16    | 1000             | Form corner steel | 7.28 | 1.37 | 3.33 | 3.59 |
| DA-8      | 325              | 1500             | Form corner steel | 8.37 | 1.40 | 3.21 | 3.64 |
| DA-9      | 350*350*11/12    | 500              | Form corner steel | 6.38 | 1.30 | 2.95 | 3.20 |
| DA-10     | 375              | 750              | Form corner steel | 7.14 | 1.36 | 2.95 | 3.50 |
| DA-11     | 400*400*12/14    | 1000             | Form corner steel | 7.63 | 1.40 | 3.03 | 3.65 |
| DA-12     | 425              | 1500             | Form corner steel | 8.20 | 1.43 | 2.96 | 3.68 |
| DA-13     | 450*450*13/16    | 500              | Form corner steel | 5.21 | 1.20 | 1.80 | 3.35 |
| DA-14     | 475*475*14/18    | 750              | Form corner steel | 5.98 | 1.28 | 3.51 | 3.41 |
| DA-15     | 500*500*15/20    | 1000             | Form corner steel | 6.49 | 1.33 | 3.63 | 3.23 |
| DA-16     | 525              | 1500             | Form corner steel | 7.11 | 1.38 | 3.75 | 3.39 |
| DA-17     | 550*550*16/22    | 500 Span 30 m    | Form corner steel | 12.10 | 1.88 | 2.61 | 5.13 |
| DA-18     | 575              | 750 Span 30 m    | Form corner steel | 13.92 | 1.99 | 5.13 | 4.43 |
| DA-19     | 600*600*17/24    | 1000 Span 30 m   | Form corner steel | 15.17 | 2.07 | 5.56 | 4.74 |
| DA-20     | 625              | 1500 Span 30 m   | Form corner steel | 16.70 | 2.15 | 5.54 | 4.98 |
| DA-21     | 650*650*18/26    | 500 Vertical member Sea | 8.85 | 1.37 | 3.29 | 3.34 |
| DA-22     | 675*675*19/28    | 1000 Vertical member Sea | 7.47 | 1.36 | 3.15 | 3.32 |
| DA-23     | 700*700*20/30    | 1500 Vertical member Sea | 7.49 | 1.39 | 2.79 | 3.36 |
| DA-24     | 725*725*21/32    | 1000 Vertical member Sea | 6.36 | 1.32 | 3.38 | 3.27 |
| PA-2      | Conventional ACS |                  |              | 10.53 | - | 6.76 | - |

Figure 16. Wind pressure – maximum displacement.

Figure 17. Wind pressure – maximum stress.
Accordingly, in this study, a design equation to calculate the maximum displacement of the formwork and the stress of form ties according to their spacing was proposed.

(3) As a result of analysis of wind loads of 30 and 35 m/s prescribed by the KBC for wind loads that may occur during the lifting of the formwork, it was confirmed that displacement and stress can be controlled more than the existing ACS. It could be seen that wind loads were greatly affected by the type and installation spacing of horizontal members.

(4) The type and installation spacing of horizontal members have large effects on the weight of the entire formwork system, and accordingly, it was identified that installing horizontal members of 200*200*8/12 at 1 m distances was the most appropriate for a 20 m span formwork system and that as the span increases, the size of the cross section should be increased. In this case, the weight of the formwork system was about 40 ~ 50 kg/m², which is about 50% of the unit weight of the existing ACS. Therefore, it could be seen that the burden of lifting could be reduced.

(5) In this study, the constituent members of the formwork were designed by assuming the end steel plate with sufficient strength and stiffness. Therefore, if the rigidity of the end support is insufficient or the configuration of the member is changed, it is determined that additional review is necessary.

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