Introduction

In tall building construction, the construction of the core structure, including the core wall and slab, is a crucial factor for successful project completion. The core structure normally acts as the main structure for resisting lateral forces such as wind and earthquake loads in tall buildings. In addition, the critical path in structural framework tends to be based on the construction of the core structure because the erection work of structural elements with a greater workload must be repetitively performed in a smaller workspace compared to the works for other structural frame elements. Thus, the adoption of an appropriate construction method for the core structure process is very important in terms of both the structural aspect of the building and the schedule estimation (Hong et al. 2011).

Currently, in most tall building construction sites in Korea, the core structure preceding construction method (CSPCM) is applied. In the CSPCM, the core structure is generally constructed five to six floors ahead of other structural frames within the perimeter zone. That is, in steel-reinforced concrete structures, the steel erection works are conducted five to six floors below the floor where the core structure construction is in progress; the installation work of the slab decks and concrete pouring works is then conducted after the steel works. By applying the CSPCM, the managers can more easily control the subsequent activities because the complex activities of the core structure are finished ahead of activities of typical working floor. This method can also facilitate the adoption of system forms such as auto climbing systems (ACSs) to reduce the workload of the core construction (Ahn 2004). However, observations on construction sites in which CSPCM is adopted show that CSPCM causes several issues in terms of construction management such as limited workspace, interference between activities, and difficulties in wall and slab joint construction. For more efficient application of the CSPCM, existing studies mainly focused on suggesting technical, structural, and managerial principles or measures (Ahn 2004; Chang 2004; Hong et al. 2011; Koo 2003; Kook 2004; Moon 2007). However, a few efforts have been made to investigate alternative construction methods to the CSPCM that can fundamentally provide a more rapid and stable working environment.

This study introduces a new core structure construction method, named the core structure succeeding construction method (CSSCM), for tall buildings in order to address the issues involved with the existing method. The study also illustrates the technical details and compares results with the CSPCM in an application to an office building of 55 stories aboveground. The study discusses technical and practical considerations to help engineers and managers apply the CSSCM in tall building construction.

Core Structure Construction Methods

Limitations of CSPCM

The CSPCM can cause several issues in terms of construction duration, costs, safety, and quality. First, the CSPCM relies heavily
on tower cranes for lifting materials and equipment, from rebars to portable urinals. This heavy reliance on tower cranes often causes delays in the total construction duration. Second, the workspace available for core structure construction becomes very limited. The construction quantities for the core areas are highly concentrated relative to the ratio of the core portion to the total floor areas. Thus, by preceding the core structure construction, the very limited workspace can cause productivity losses and safety problems such as falling accidents. Third, interference between activities is likely to occur. In the CSPCM, as the heights of tall buildings increase, ACSs are widely applied for the construction of vertical structures, including core walls (Kim et al. 2007). For safety reasons, the steel erection work on the perimeter zone should cease during the climbing work of the ACSs attached to the external core wall. This causes productivity losses. This method also leads to cost increases due to increased inputs of temporary facilities such as the ACSs, the temporary fire prevention and fighting system in the ACSs, and temporary lift cars for core access. Finally, CSPCM requires intensive management of the joints between core walls and steel members. In the CSPCM, plates for connecting the steel girders and beams are embedded into the core walls before concrete placement. Thus, the construction accuracy of these members largely affects the construction duration, structural safety, and quality of the structure. Even though these shortcomings can be partially alleviated by careful planning and management, the increased size and height of tall buildings requires a more innovative construction method for the structural framework.

Core Structure Succeeding Construction Method

The construction processes of the CSPCM are reversed in the CSSCM. That is, the structural framework of the steel-reinforced concrete structure using the CSSCM is completed in four steps as follows: (1) erection columns and girders are erected around the core zone to connect with the steel frames in the perimeter zone; (2) the steel erection work on the perimeter zone is completed; (3) the installation and concrete placing of slab decks are generally completed two to three floors behind the floor where steel work is progressing; and (4) the rebar, formwork, and concrete placing operations of the core structure progress four to five floors later than the steel work of the perimeter zone.

Based on this procedure, the CSSCM can overcome most issues involved with the CSPCM. First, the perimeter zone can be utilized as both stockyard and workspace. Because the structural framework on the perimeter zone precedes the core structure work, workers can use the spaces of the deck slabs for the rebar and formwork operations of the core structure as well as equipment operations such as tower cranes and concrete placing booms. This leads to improvements in the productivity and safety of the construction of the core structure. Second, handset forms such as aluminum forms are adopted instead of the ACSs for the exterior formwork of the core structure. Aluminum forms are the most preferred for tall building construction in Korea because skilled laborers are readily available and the forms are applicable to all structural types (Kim et al. 2012). Thus, the utilization of aluminum forms can be a useful way to meet the requirements of both productivity and economic feasibility. Third, in the CSSCM, the construction of joints between core walls and steel frames becomes much easier than that in the CSPCM. The adoption of the CSSCM does not require the installation of embedded plates and Halfen boxes for connecting steel girders or the rebar of slabs to the perimeter zone. This enhances not only management performance, but also structural safety and quality.

Case Study

Case Description

The case used in this study is a 55-story office building located in Yeouido-Dong, Seoul with a steel-reinforced concrete structure. As shown in Fig. 1, the dimensions of typical floors and the core zone are 65.3 m long and 38.3 m wide and 48.5 m long and 12.8 m wide, respectively. The core floor plans change on the 22nd, 34th, and 45th floors. The outrigger trusses acting as lateral force resistance are located on the middle floors (20th–22nd floors) and on the 9 m above the 54th floor. A helipad, gondola rail, and cooling tower constructed of steel trusses weighing approximately 1,000 t are

![Fig. 1. Section and floor plan of the case: (a) sectional plan; (b) floor plan of a typical floor](image-url)
installed over the roof level. The adoption of the CSPCM would lead to a delay in construction duration because of the need for a large number of connection works between the core and perimeter zone on the outrigger floors. Moreover, for the case building, the construction time needs to be reduced by approximately four months to meet the contract duration. For these reasons, the contractor decided to apply CSSCM rather than CSPCM after a comparative review of both methods.

**CSSCM Application**

Fig. 2 shows the construction methods and procedure of the structural framework for the case building applied from the sixth floor. Considering the efficient equipment operations, the steel framework of the perimeter zone was completed five floors ahead of the core structure work. Compared to the CSPCM method, these preceding works required additional steel frames of approximately 711 t for the erection girders and columns. The 182 t of rebar required for the CSSCM method was reduced with the CSPCM method because the embedded plates and Halfen boxes were not needed, and because the structure of link beams changed from reinforced concrete to steel-reinforced concrete; the link beams of the core walls can be constructed effectively using erection girders. Aluminum forms were adopted for the exterior formwork of the core structure instead of the ACSs. Because the formwork operation is performed on the deck slabs, easier and safer erection work is possible. Angles and plates (Fig. 3) allow the absorption of construction errors and facilitate correction work on the floors where the core wall thickness and the floor plan change.

Two tower cranes and two concrete placing booms were installed in the core zone (Fig. 4). The tower cranes, with an overhang of 36–42 m, were used because they should be located above the maximum height of the steel frames. The concrete placing booms were fixed at the N-1 and N-2 levels and located up to the N + 2 level for concrete pouring on the deck slabs and core structure (Fig. 5). Their Z-type boom enables bending in any direction between the steel frames for efficient concrete placing work. The perimeter zone where structural framework is completed can provide a safe working area for installing and lifting the equipment. The number of temporary lift cars usually needed for construction can also be reduced because extra lift cars for the core structure work is unnecessary. For this case, two lift cars of twin type were installed only on the perimeter zone.

External protective measures with a self-climbing system were installed to provide a safe and optimal working environment for concrete placing and curing, fireproofing, and electrical and plumbing work. Curtain wall installation progressed on two floors below the protective measures.

**Comparison of Schedule and Cost**

Fig. 6 and Table 1 compare the changes in construction durations of tasks when applying the CSSCM and the CSPCM. The comparison shows that the CSSCM can lead to substantial reduction in construction duration compared with the CSPCM for the following reasons: (1) the use of aluminum forms on the exterior core walls reduced the ACS setting and disassembly works as well as the modification work on the floors where the core floor plan changes; (2) the lack of need for embedded plates and the provision of a stable working environment on the deck slabs enhanced the productivity of the working trades including outrigger erection; (3) steel frame work for the roof level started earlier because the work could...
proceed regardless of whether the core work has been completed; and (4) the earlier completion of the steel frame work eliminated the delay on starting the curtain wall installation on the roof level. Consequently, the total duration from structural steel (from sixth floor) to finish works by applying the CSSCM was 22.6 months, which was 4.9 months (calendar days) less than when applying the CSPCM.

Table 2 shows the cost changes by applying the CSSCM compared with the CSPCM. For the case building, the CSSCM can save approximately $7.5 million over the CSPCM due to the following
factors: (1) the cost of the embedded plates and Halfen boxes is eliminated; (2) steel erection work becomes much easier, which results in a reduction of the erection cost by approximately US $240 per ton; (3) installation of the extra lift car for transporting resources to perform works in the core zone is unnecessary. In addition, the rental duration of the equipment, including the ACSs, concrete placing booms, lift cars, and tower cranes, can be reduced by approximately 1.5–4.9 months due to the expedited construction duration; (4) concrete placing work can be performed by fewer workers (reduction of four workers per floor) due to the enhanced work efficiency of the concrete placing booms; (5) material and operating costs of the ACSs, gang forms, and scaffolding for the exterior core structure can be reduced; (6) one hundred eighty-two tons of rebar for link beams can be reduced because the erection girders also function as link beams; and (7) the expedited construction duration leads to indirect cost savings. However, the CSSCM incurred extra costs of approximately US $2.1 million for erecting additional resources (erection columns and girders, and aluminum forms) and for the review of the structural safety and redesign of the structure. However, the actual cost saving would be more than the estimated value because the cost for reviewing the structural safety and redesign of the structure was incurred by changing the construction method from CSPCM to CSSCM; if the change was not necessary and CSSCM was planned from the design stage, this cost would be reduced.
Table 2. Cost Changes by Applying CSSCM Compared to CSPCM

<table>
<thead>
<tr>
<th>Category</th>
<th>Items</th>
<th>Cost changes (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items causing cost reduction</td>
<td>Omission of embedded plates and Halfen boxes</td>
<td>531,584</td>
</tr>
<tr>
<td></td>
<td>Enhancement of working environment for steel frame installation</td>
<td>3,231,342</td>
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<tr>
<td></td>
<td>Reduction of rental duration and the number of equipment</td>
<td>349,211</td>
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<tr>
<td></td>
<td>Operating efficiency improvement of concrete placing booms</td>
<td>40,727</td>
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<tr>
<td></td>
<td>Reduction of the number of ACSs, gang forms, and scaffolding</td>
<td>891,795</td>
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<tr>
<td></td>
<td>Rebar reduction of link beams</td>
<td>148,909</td>
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<td></td>
<td>Reduction of construction durations</td>
<td>4,454,545</td>
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<td></td>
<td>Subtotal (a)</td>
<td>9,648,114</td>
</tr>
<tr>
<td>Items causing cost increase</td>
<td>Steel frames for the erection columns and girders</td>
<td>1,058,856</td>
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<td></td>
<td>Formwork operation using aluminum forms</td>
<td>591,075</td>
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<td></td>
<td>Installation of construction joints</td>
<td>102,195</td>
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<td></td>
<td>Review for structural safety</td>
<td>363,636</td>
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<tr>
<td></td>
<td>Subtotal (b)</td>
<td>2,115,762</td>
</tr>
<tr>
<td></td>
<td>Total [(a)–(b)]</td>
<td>7,532,352</td>
</tr>
</tbody>
</table>

Despite remarkable performance enhancement in terms of time and cost, observation and experience from the case project show that engineers and managers should carefully consider the following aspects in order to adopt the proposed method effectively. In engineering terms, special level-adjusting elements need to be considered in the design process to allow the absorption of construction errors as well as facilitate the correction work while erecting hand-set forms for the exterior formwork of the core structure. In terms of the construction management, it is very important to control the shortening of the erection columns buried in the core wall because they are relatively slender compared to the steel frames on the perimeter zone. Finally, the proposed method requires closer cooperation and collaboration among trades involved in the structural framework because the works on the perimeter zone can precede the core works only for a maximum of nine floors.

Conclusions

This paper introduced a new core structure construction method for tall buildings, the CSSCM, especially with a steel-reinforced concrete structure, to address the issues of the existing method, the CSPCM. It was successfully applied in the construction of a recently completed tall building in Korea. The study revealed that this method has the potential as an effective construction method of structural framework for tall buildings where short cycle times are required. The method is also more cost-effective than the existing method, which necessitates substantial expenditure on temporary structures for the core wall construction as well as subsidiary elements for connecting the structural members to the core and perimeter zone. In addition, the proposed method can provide stable working environments for steel erection including for outriggers and core works. The illustrative application described in this paper will assist engineers and managers to apply this construction method appropriately to similar projects and to deal with flexible changes in building design and engineering technologies. We will continuously carry out extended cost-benefit analysis including safety and quality aspects based on additional cases as well as process improvement for broad industry deployment.

Acknowledgments

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References