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MODULARIZED TOP-DOWN CONSTRUCTION TECHNIQUE USING SUSPENDED POUR FORMS (MODULARIZED RC SYSTEM DOWNWARD, MRSD)

WON-KEE HONG, JIN-MIN KIM*, HO-CHAN LEE, SEON-CHEE PARK,
SEUNG-GEUN LEE AND SEUNG-IL KIM
Department of Architectural Engineering, Kyung Hee University, Gyeonggi-do, Korea

SUMMARY

Propping systems utilizing permanent slabs have been used for many decades around the world to resist lateral soil loads on piled perimeter walls or diaphragm perimeter walls during basement excavation. In the top-down construction technique, when the excavation starts to break ground and the placement of the ground level slabs is complete, upward construction of the superstructure while digging the basement are carried out simultaneously. However, the conventional top-down method requires slabs poured on excavated soils. This process of installing and removing temporary supports is difficult and dangerous, often resulting in a delayed excavation and construction schedule. The objective of this paper is to present an innovative deep basement top-down construction technique that eliminates conventional temporary supports through the use of hanging pour forms. The weight of the concrete that is cast for forming slabs is supported by the hanging pour forms. This technique utilizes permanent metal deck plates located on the edges of the pour forms. The many advantages of this technique over the conventional top-down method are described. This paper also describes the first project application on which the new technique was used to separate the concrete work from the excavation. Copyright © 2009 John Wiley & Sons, Ltd.

1. INTRODUCTION

For many decades, the so-called top-down technique has been used as an affordable construction solution for deep excavations in densely populated cities. These buildings often have multiple underground levels for parking, mechanical plant, storage and leisure facilities. While this technique is safe and convenient for construction of deep underground structures, the excavation and concrete work, including the installation of concrete pour supports for the concrete forms, cannot be carried out simultaneously.

Many research investigations have focused on effective construction techniques for underground structures. These studies include the construction of underground structures with flat slabs and the use of glass fibre-reinforced polymer (GFRP) for slabs, providing a new top-down technique for building underground structures with deep excavations. Hong *et al.* (2005) described this construction technique using permanent steel frames and its advantages over temporary propping systems that must be removed after excavation is finished. Lee *et al.* (2008) summarized full-scale test results of a concrete-filled tube column connected to reinforced concrete (RC) flat plates subjected to gravity loading. Sahab

*Correspondence to: Jin-Min Kim, Department of Architectural Engineering, Kyung Hee University, Gyeonggi-do, 446-701, Korea. E-mail: kimjm@khu.ac.kr

et al. (2005) performed cost optimization comparing the results of the optimum and conventional design procedures for three RC flat slab buildings. El-Ghandour *et al.* (1998) reported on an experimental program aimed at investigating the structural behaviour and design of fibre-reinforced polymer concrete flat slabs with carbon fibre-reinforced polymer (CFRP) shear reinforcement. El-Ghandour *et al.* (2003) also presented the results of a two-phase experimental program investigating the punching shear behaviour of fibre-reinforced polymer RC flat slabs with and without CFRP shear reinforcement. In 2004, both experimental and analytical investigations of the axial behaviour of large-scale circular and square concrete columns confined by carbon composite tubes were presented by Hong and Kim (2004). In addition, full-scale samples of these concrete-filled carbon composite tubes, with various winding angles of the carbon fibres measured with respect to the longitudinal axes, were subjected to varying lateral loads and a constant axial load (Hong *et al.* 2004).

Considerable research has focused on providing diverse methodologies for both the shortening of construction schedules and the lowering of construction costs.

An analytical investigation estimating the strength degradation of the composite beams was based directly on the post-yield behaviour of the composite structure as a function of ductility. This study was carried out by Hong *et al.* (2009a). Full-scale composite beams composed of wide flange steel beams, with the bottom flange encased in precast concrete, were tested by Hong *et al.* (2009b) to determine the load-carrying capability of the beams at both the yield and the maximum load limit states.

The temporary supports cannot be removed until the concrete is sufficiently cured and can resist the self-weight and construction vertical loading along with the in-plane axial loading from the lateral foundation walls. Such a system typically delays excavation.

This paper presents the first application of the proposed system on a six-level basement for an office building in Seoul, Korea. In this application, flat concrete slabs in lieu of slabs with beams were designed to reduce floor-to-floor height, resulting in a decrease in the required soil excavation and a shortened construction schedule. The utilization of a suspension structural system provided space for excavation and convenient access to the disposal of excavated soil as well. The efficiency and safety of the workplace was considerably enhanced. Hanging pour forms with a metal deck plate eliminated the use of the conventional supports, enabling excavation to be carried out separately from the concrete pouring. The steel rods were installed only in the column strip where the pour forms were assembled. In the middle strip, the metal deck plates were located along the edge of the pour forms to support the weight of the concrete. No conventional supports were used under the pour form or for the metal deck. GFRP was used as surface material of steel frame pour forms to be easily detached from cured concrete surface.

2. BIRTH OF CONCEPT

Figure 1 describes the advantage of the new technique over the conventional technique, in which levelling concrete placed on the excavation subgrade is used as a temporary support for the concrete slab formwork system. Construction schedule can be significantly reduced when excavations and concrete pouring are done simultaneously.

The locations of the steel rods were limited to the column strip, where pour forms were also installed and detached, shortening the construction schedule. The permanent self-supported metal deck plates were installed along the edges of the GFRP pour forms in the middle strip as shown in Figure 1(b), eliminating the use of time-consuming pour forms. The flat GFRP pour forms detached easily, providing the flat slab that contributed to the reduced floor-to-floor height. The pour forms manufactured of GFRP with a steel frame provided easy, fast installation and removal from the cured flat concrete surface.

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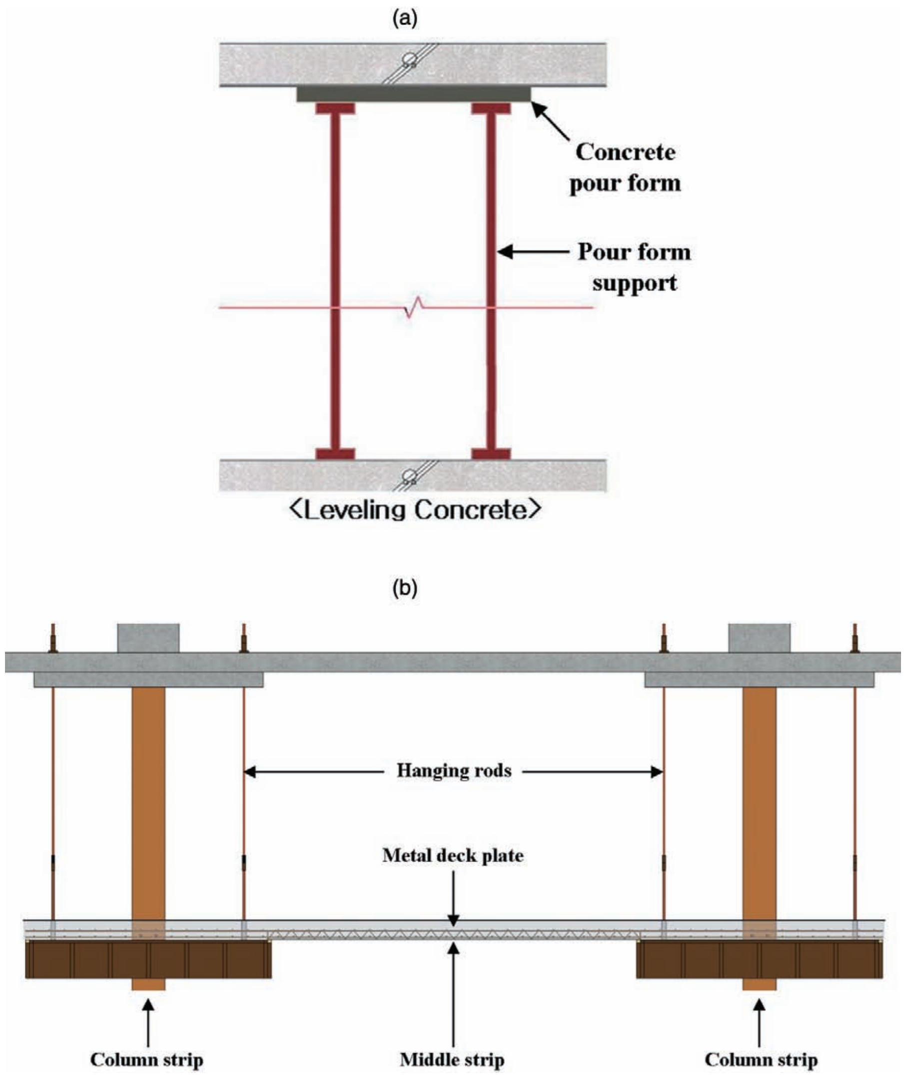


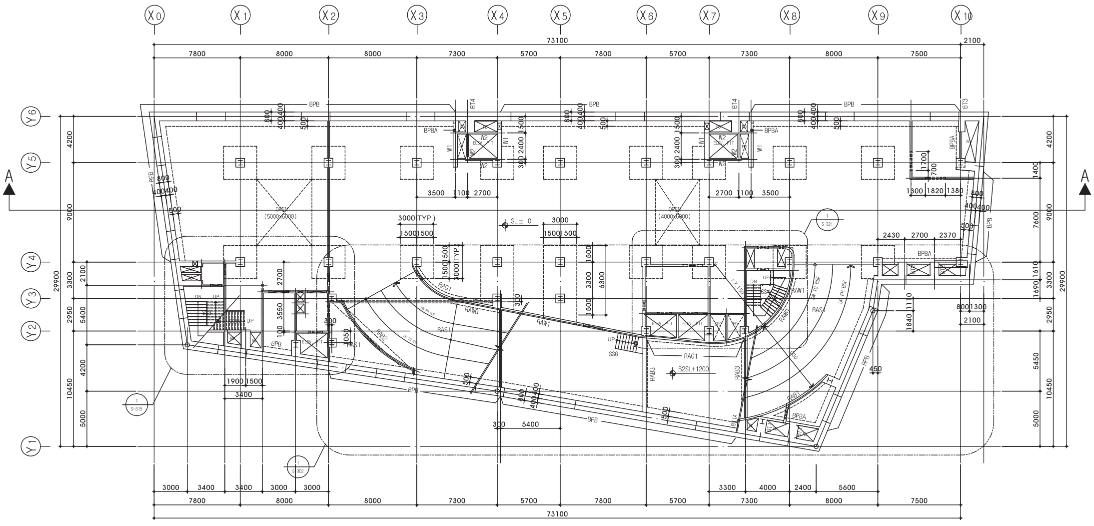
Figure 1. Advantage of the new technique. (a) Support system. (b) Modularized reinforced concrete system downward hanging system

3. APPLICATION OF THE SYSTEM TO A SIX-STOREY UNDERGROUND STRUCTURE

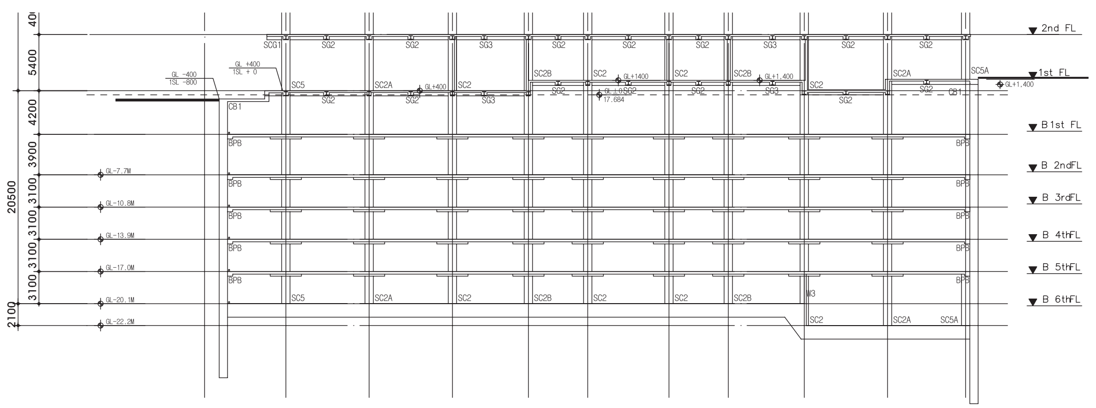
3.1 General information regarding the underground structure

This paper presents the first application of this new building system on a six-level basement for an office building in Seoul, Korea. This structure required a 23·5 m deep excavation. The site was 29·9 m wide by 75·2 m long. The basement floor plan of the 19-storey building is shown in Figure 2.

The diaphragm wall was sized and reinforced to resist lateral soil pressures during excavation. The height excavated without lateral props reached 4·6 m, including the floor height of 3·1 m for the exterior region adjacent to the diaphragm wall. The excavation was carried out to a height of 7·7 m without lateral props for the interior region of the site. Construction began with installation of the perimeter



(a)



(b)

Figure 2. Floor plan of first floor (basement) and section. (a) Floor plan. (b) A-A section

foundation diaphragm wall from ground level. Permanent internal steel columns were then inserted into 500 mm diameter holes drilled using a small rotary piling rig, after which concrete was delivered via a tremie to the bottom to provide end-bearing resistance. The steel columns installed into the predrilled holes were required to meet a verticality tolerance of 1 in 300. The steel columns provide a more economical alternative to that of conventional top-down construction, which typically utilizes large bored piles of 2–3 m in diameter to carry loads from slab and superstructure. An important design criterion of this method was the prevention of the buckling of the vertically preinstalled steel columns due to construction loading during excavation.

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3.2 Construction schedule of one cycle

The construction schedule for one cycle, consisting of typical floor, is shown in Figure 3. The construction of a typical floor required 32 days for completion of one cycle from excavating to the curing of the concrete. The complete cycle also included the removal, descending and reinstalling of pour forms. Six days were added for descending, maintaining and repairing the GFRP pour forms, resulting in a total construction time for one floor of 38 days. It was recognized that the systematic repetition of the installation, removal and descending of pour forms shortened the construction schedule significantly. The additional 13 days were required to locate and install pour forms in the first basement level prior to the commencement of the excavation.

Figure 4 describes the construction schedule for one floor. Figure 5 shows the site divided into two regions in which excavation, removal of pour forms and concrete casting and curing were carried out alternately. The construction joints were formed at the boundary between zones A and B.

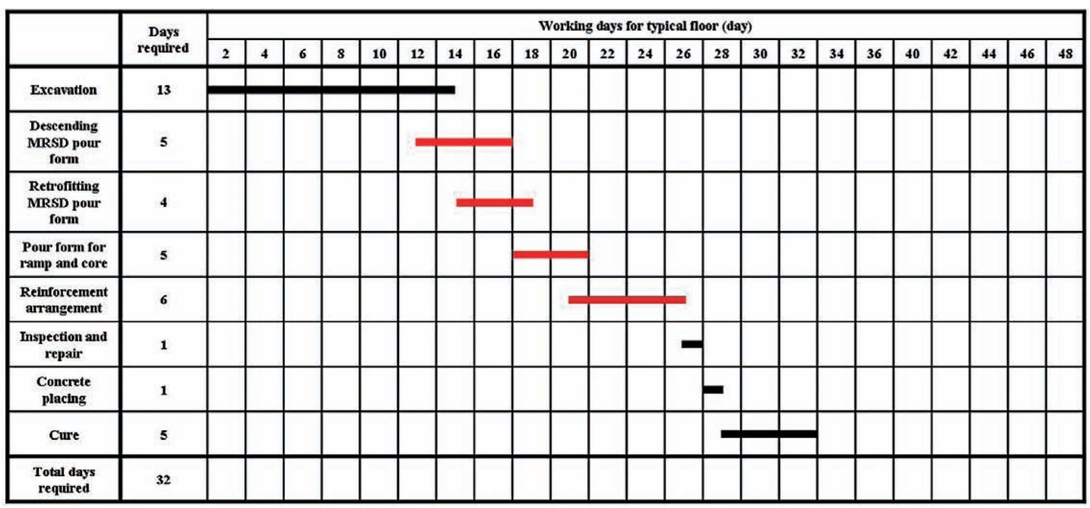

Figure 3. Construction schedule of one cycle (typical level)

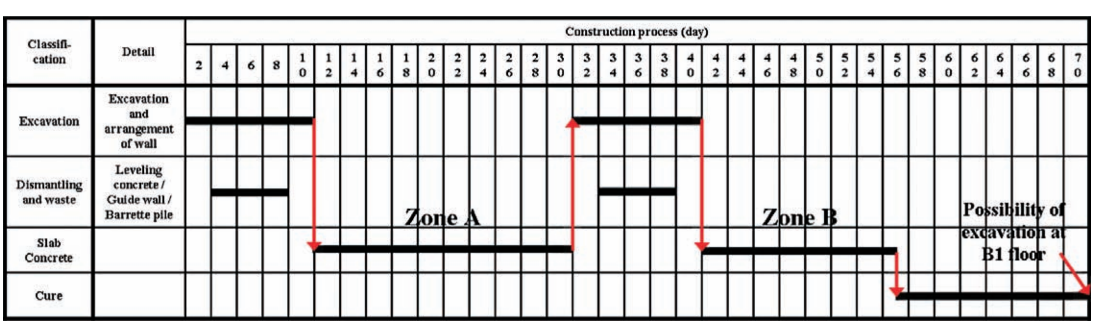

Figure 4. Construction schedule for one floor

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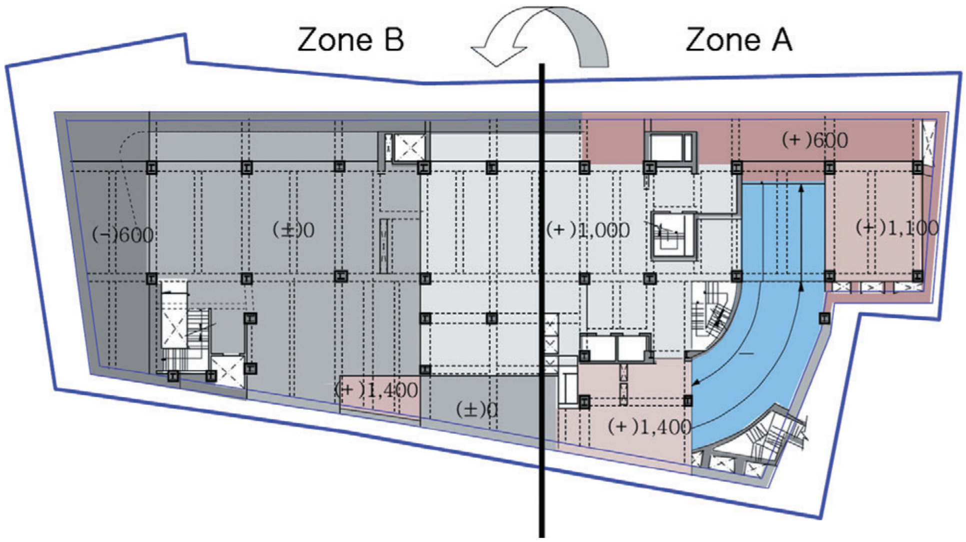

Figure 5. Divided zones for excavation sequence

Table 1. Design parameters

Column	Steel	H-498 × 432 × 45 × 70 (SM490)
	Concrete	800 × 800 mm
Foundation	Type	Mat foundation
	Bearing capacity	600 kN/m^2
	Foundation thickness	1·2 m
	Pile	Barrette pile
Slab	Slab thickness	250 mm
	Capital	Depth: 450 mm
		Width: 3000 mm
Column-capital shear connector	Headed shear studs	Four headed shear studs
		(Diameter = 16 mm, L = 75 mm)
		16 headed shear studs per column
Steel rods	Reinforcing steel with 25 mm diameter (f_y = 400 MPa)	

4. MODULARIZED TOP-DOWN CONSTRUCTION TECHNIQUE USING SUSPENDED POUR FORMS (MODULARIZED RC SYSTEM, DOWNWARD, MRSD)

Table 1 presents the general information for the structural elements used in this system, including the steel rods. Each steel rod has a yield strength of 400 MPa and a diameter of 25 mm, providing suspending force of 200 kN. The steel rods were installed every 4·5 m.

4.1 Top-down construction in the flat slab system

In this study, the flat slab construction process is presented using flat GFRP pour forms covering only the column strip. The details of the descending mechanism are introduced, including the complete cycle consisting of the descending of the pour forms, placing metal deck plates in the middle strip, curing the concrete and the excavation of the next level.

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The total number of steel rods located in the column strip was 26; six of them were used as descending pour forms by an electric crane. The rest of the steel rods were disconnected from the floor above while pour forms were being lowered by the electric crane. These steel rods were then reconnected when the pour forms were positioned at the next level for installation of the metal deck plate.

4.2 Construction sequence

Figures 6–14 show graphical representations and corresponding photographs of the construction sequence. It is noted that graphical representations were prepared to present the new construction concepts at the site. These representations were found to be useful for simulating work carried out during the construction, and they were also helpful in reducing the uncertainty involved in the new construction procedure at the site.

Figure 6 describes how excavation was carried out without being delayed by the temporary supports, which were substituted for by the steel rod hanging pour forms. The concrete and pour form work and the soil excavation were carried out simultaneously. Another advantage provided by this technique is that there was enough space for excavation and for working in safety.

The graphical and photo representations in Figure 7(a) and 7(b) shows the pour forms ready to be detached from the cured concrete surface. Figure 7(b) shows the view below the pour forms on the opposite side of Figure 8(b).

The excavation of the next level continued unhindered by the site concrete work. The fasteners were released for the six steel rods, which were then connected to the electric crane to be lowered in Figure 8(a) and 8(b). The location of these descending steel rods was carefully determined by considering the size and centre of gravity of the pour forms. These figures also show the electric crane, from which the six steel rods hung, securely supporting the self-weight and metal deck plates. In this figure, the pour forms were prepared for lowering, showing the six locations of the steel rods controlled by the electric crane. The electric crane provided sufficient power for slow and safe descending of the rods. The 20 fasteners were also released before descending commenced.

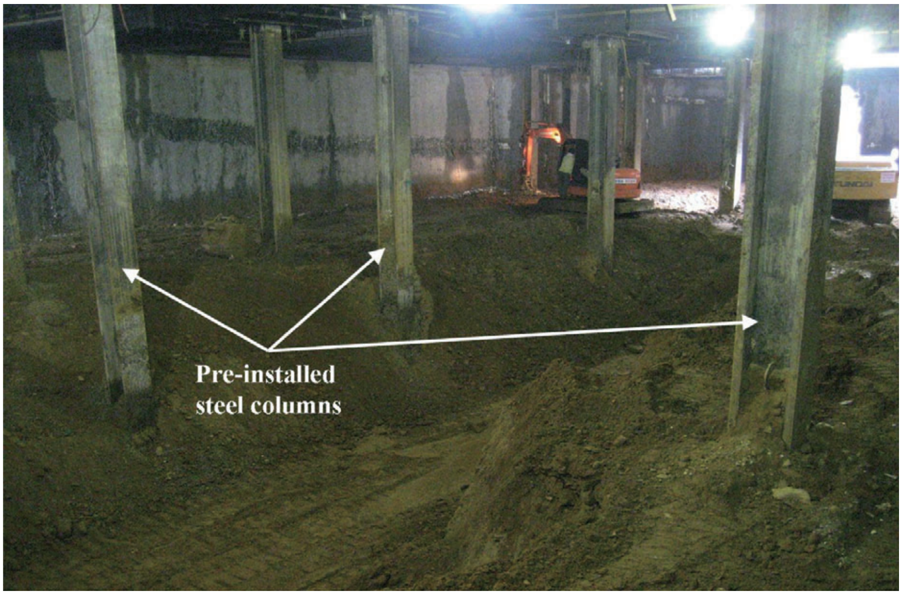

Figure 6. Excavation with no temporary vertical supports

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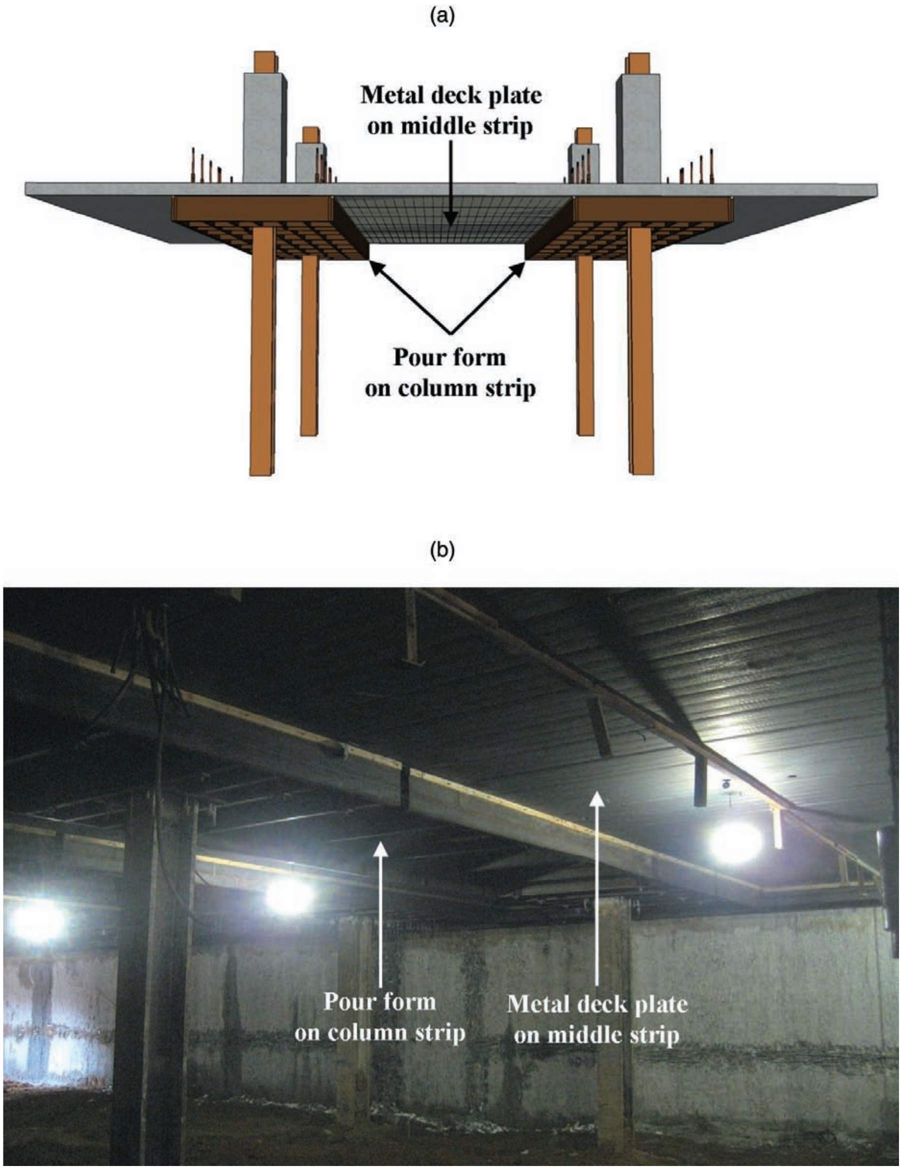

Figure 7. Pour forms ready to be detached. (a) Pour form on column strip and metal deck plate on middle strip. (b) Flat glass fibre-reinforced polymer pour form prior to removal

After this, the pour forms were detached from the cured concrete surface and lowered. They were detached by the weight of the pour forms without applying additional force.

Figure 9(a) and 9(b) shows six electric cranes positioning pour forms level with where the next floor was to be constructed. In Figure 9(b), the detached pour forms were lowered with the electric crane slowly enough to maintain a horizontal balance. Engineers below and above the slab where the six steel rods were suspended communicated with each other, finishing the whole descending process safely in 15–20 minutes. The pour forms were positioned level with where the next floor was to be

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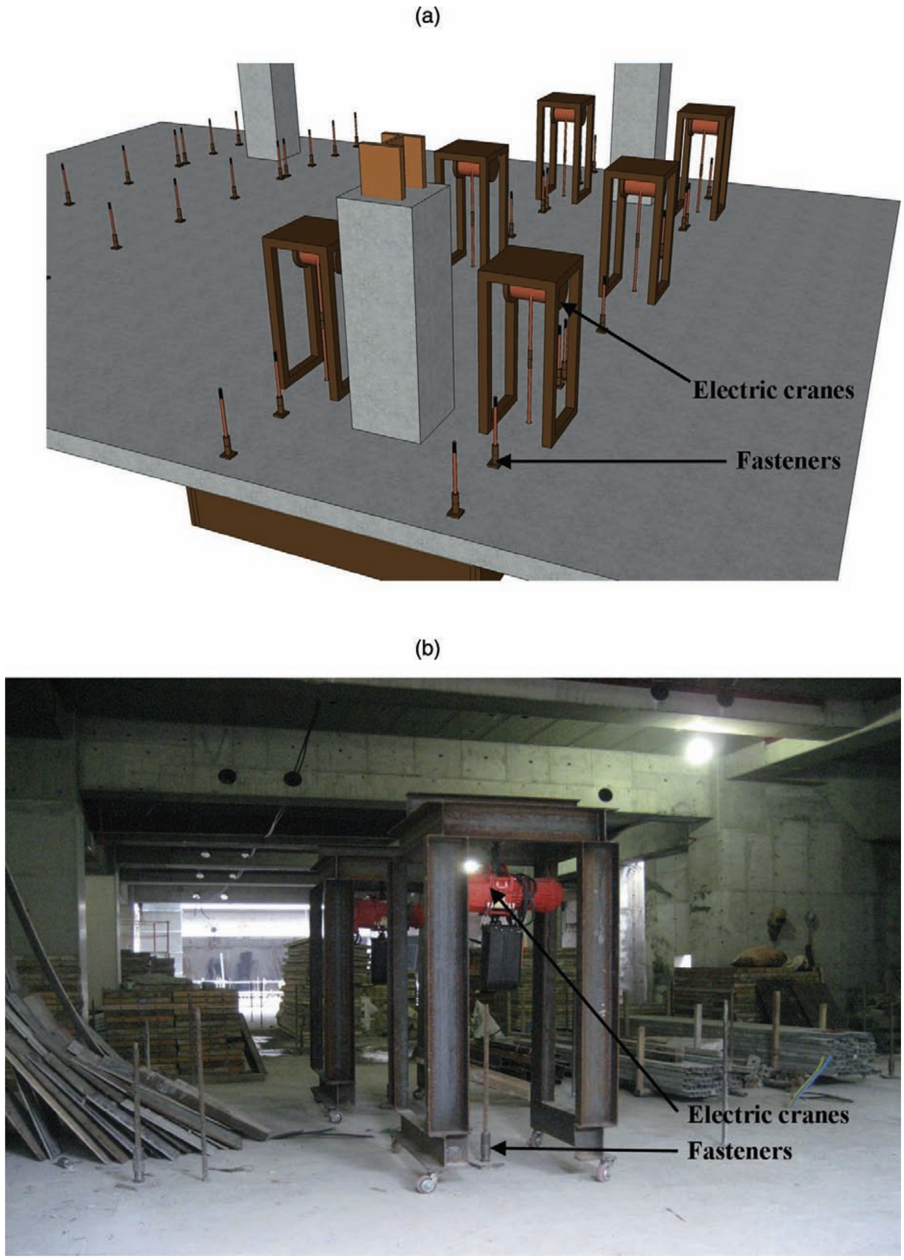

Figure 8. Preparation of electric cranes. (a) Six electric cranes ready to descend. (b) Fastening electric cranes to rods

constructed as shown in Figure 9(c) and 9(d). The level of the pour forms was constantly monitored by two site engineers until they were fixed to the preinstalled steel columns.

In Figure 10(a), steel rods not attached to the electric crane were connected to new steel rods to support the weight of the pour forms, the metal deck plate and the concrete of the next floor. Mechanical couplers were used to connect the disconnected steel rods to the steel rods provided from the

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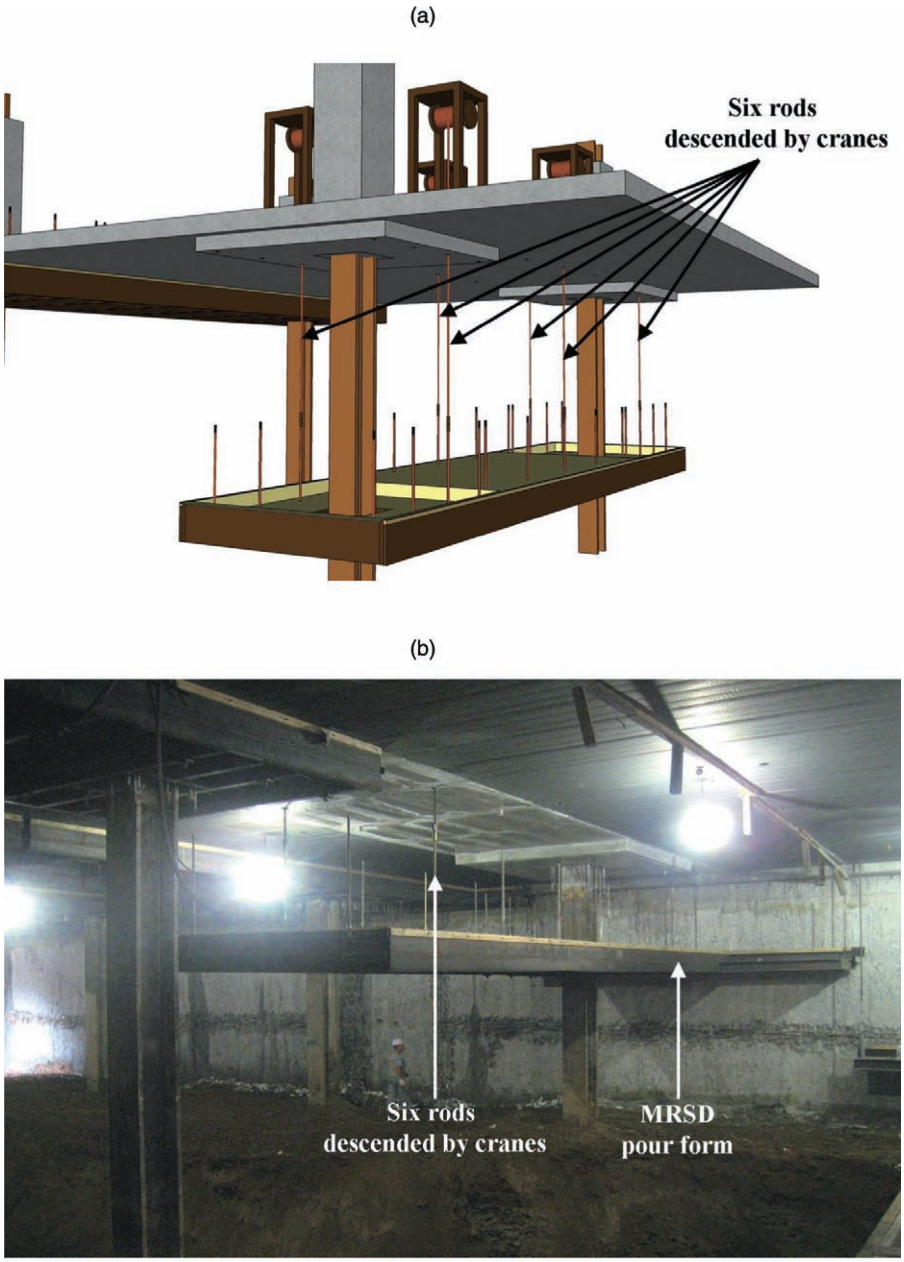

Figure 9. Modularized reinforced concrete system downward (MRSD) pour form positioning. (a) Descending of six rods. (b) Descending of flat glass fibre-reinforced polymer pour form

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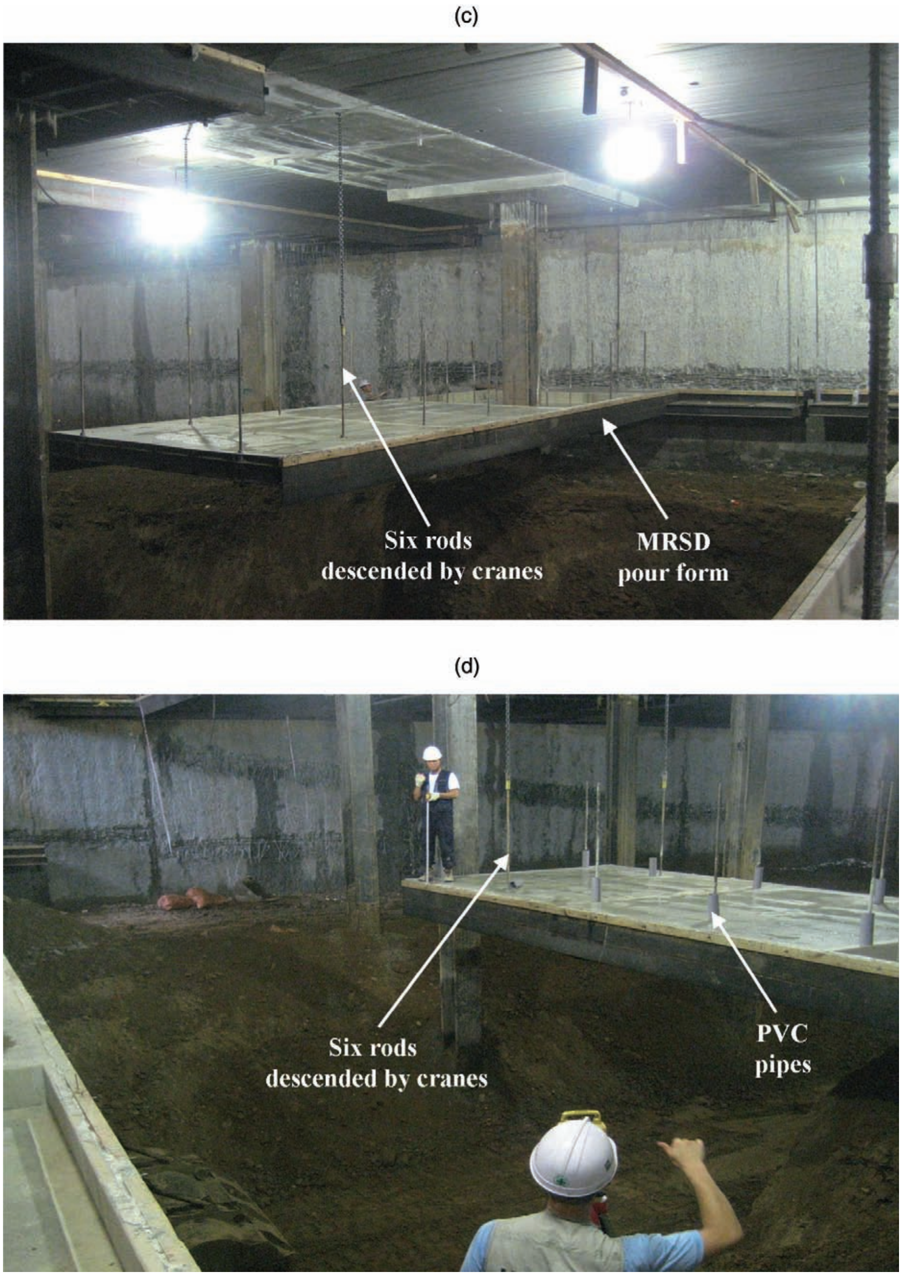

Figure 9. (c) Descended MRSD pour form. (d) Levelling of MRSD pour form

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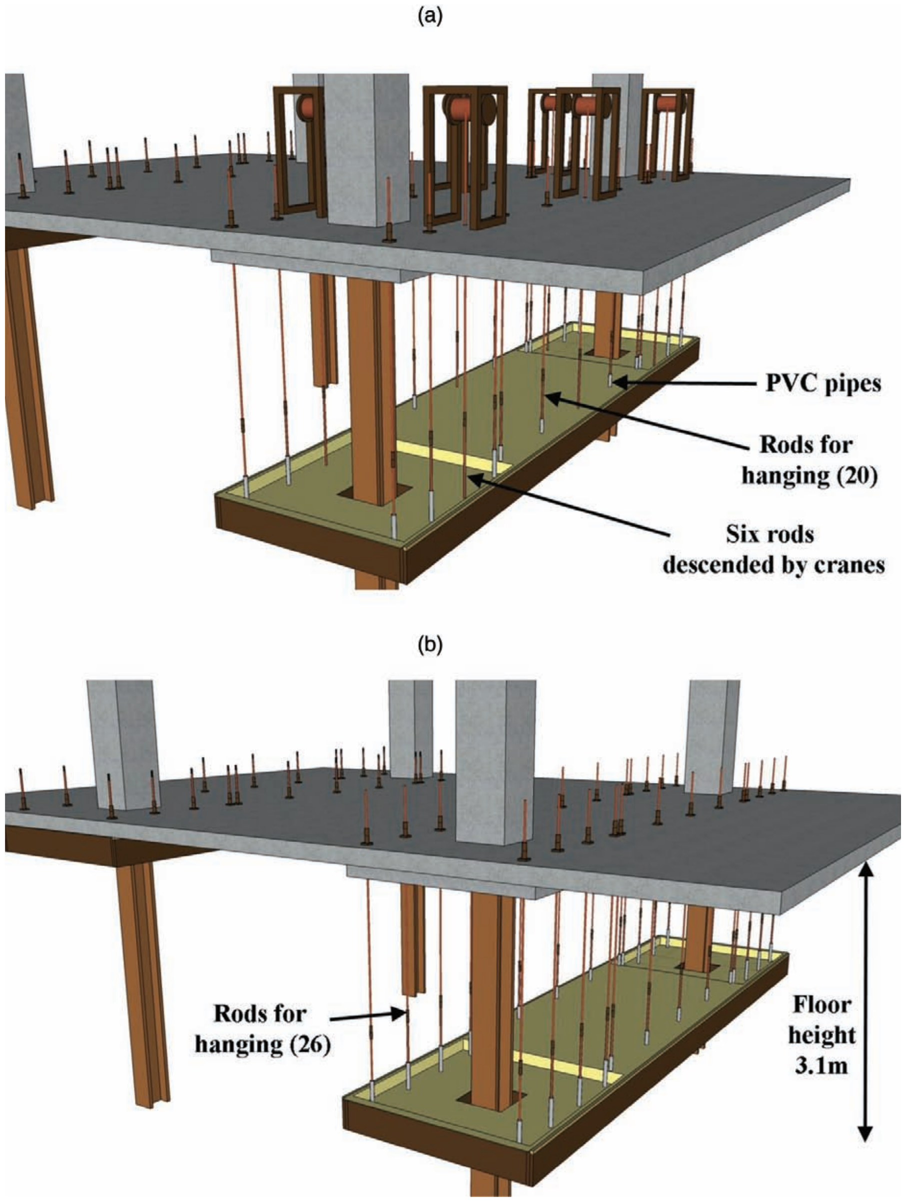
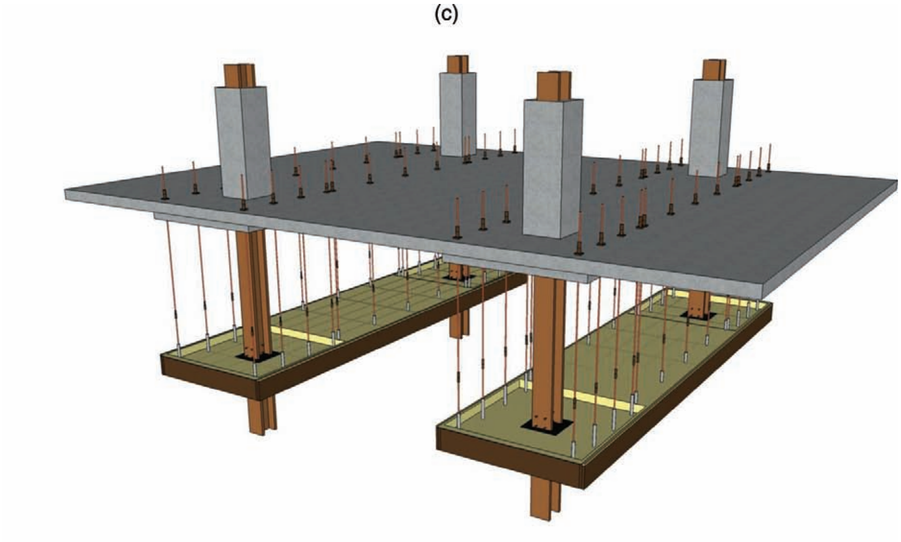


Figure 10. Reconnection of 26 steel rods. (a) Twenty rods connected. (b) Moving of electric cranes and 26 rods connected.

hanging points of the floor above. The connected steel rods held the pour forms. The level of the pour forms was monitored accurately by adjusting fasteners on the cured concrete slab. The polyvinyl chloride pipes were used to provide free movement of the steel rods when the detached pour forms were being lowered.

In Figure 10(b), the electric crane was moved to the next lower floor to prepare for another descending. All of the steel rods, including the six rods disconnected from the electric crane, were connected

(c)



(d)

Figure 10. (c) Two flat modularized reinforced concrete system downward pour forms positioned. (d) Reconnection of rods

back to the rods to support the construction loading of the next floor. All of the bolts were once again fastened to support the construction loading, including the weight of the concrete.

Two pour forms in each column strip were prepared for the installation of the metal deck plates in the middle strip for the next floor as shown in Figure 10(c–e).

In Figure 11, pour forms were fixed to the steel column to keep the pour forms from moving in the transverse direction after the descended pour forms were positioned. The movement of the pour forms was restricted by fixing the pour forms to the preinstalled steel columns through the wood tie. Wire

(e)

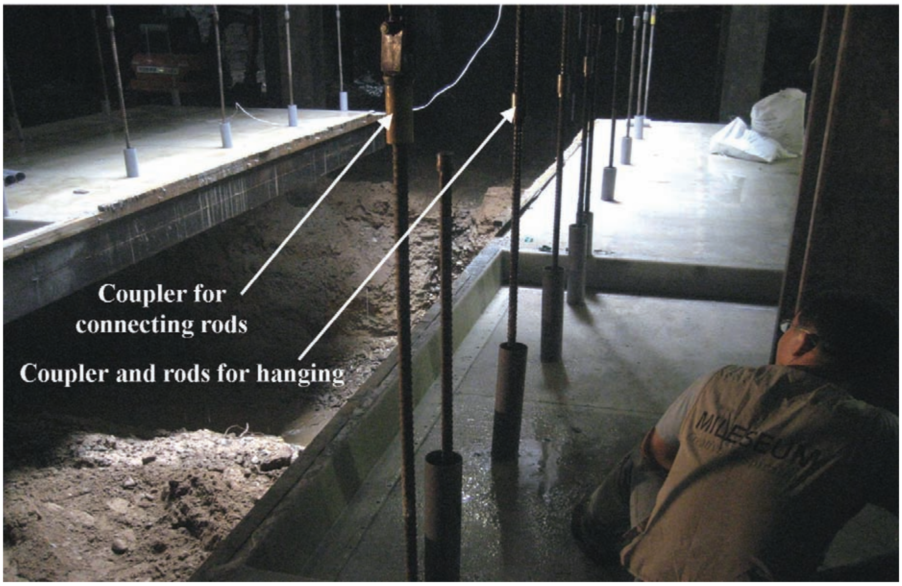


Figure 10. (e) Details of connections

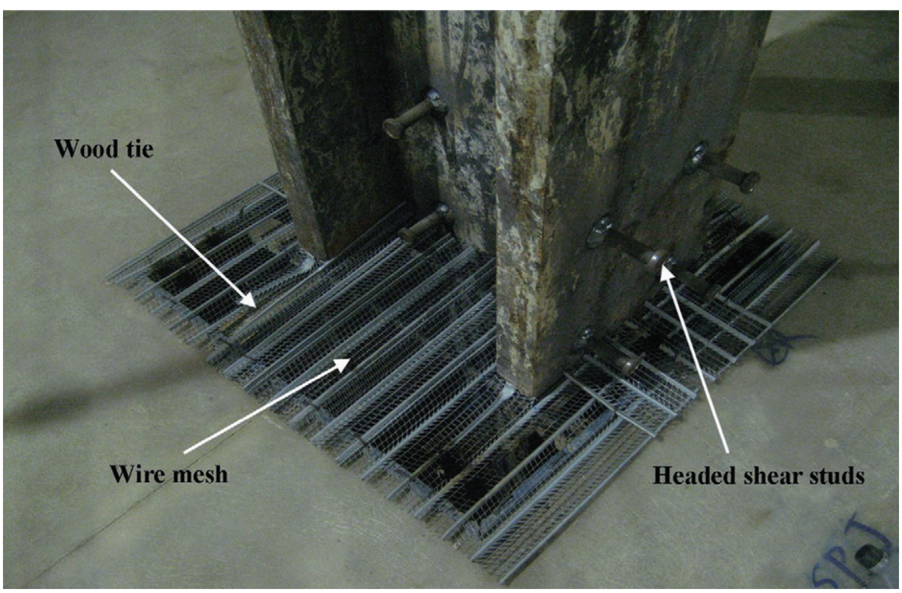


Figure 11. Slab-column joint

mesh and headed shear studs on the steel columns and vertical steel reinforcement were installed to provide monolithic behaviour of the slab-column joint.

Figure 12(a) and 12(b) shows the metal deck plate in the middle strip located along the edges of the two pour forms. The metal deck plates and the pour forms were fixed to keep the relative movement from moving when the concrete was poured.

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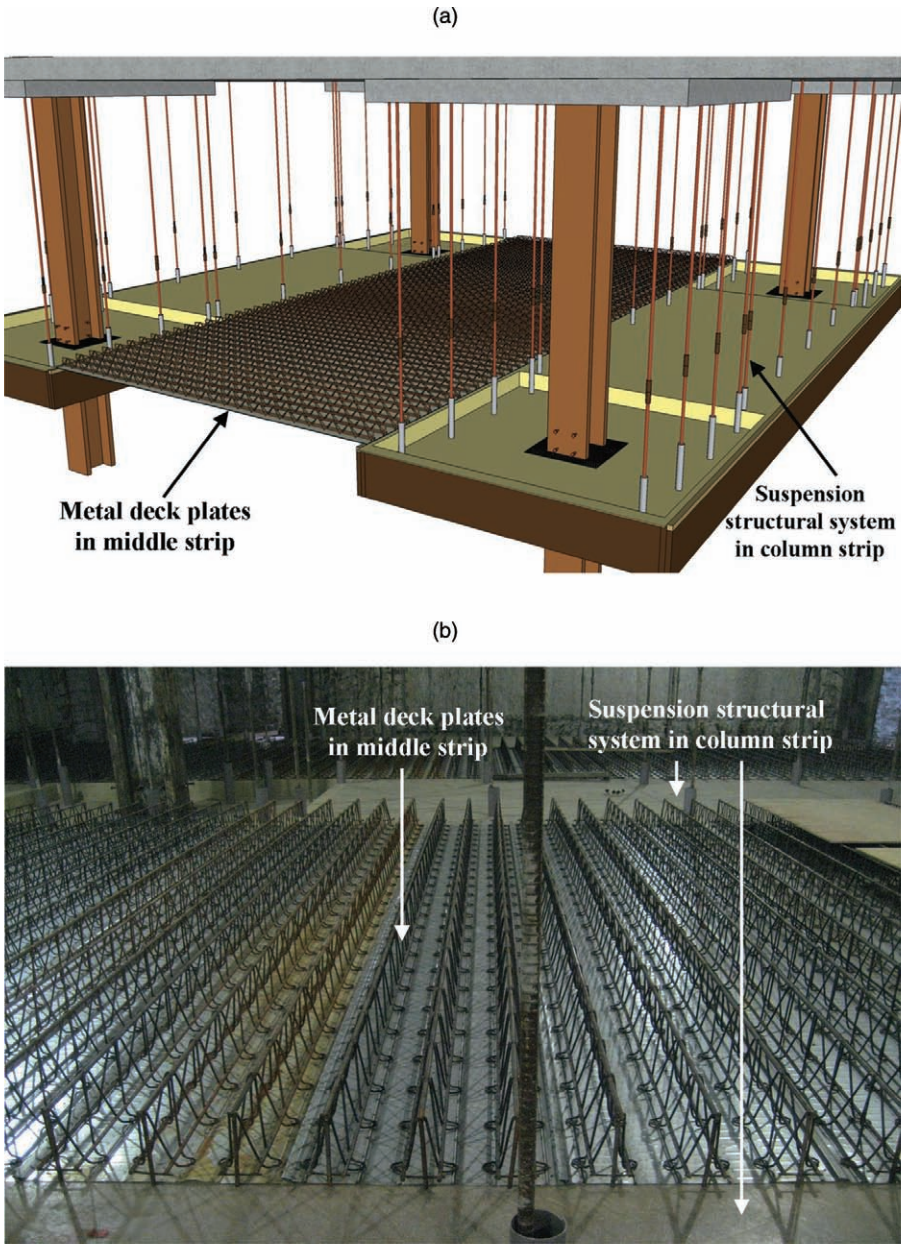

Figure 12. Metal deck plates in middle strip. (a) Metal deck plates for concrete. (b) Metal deck plates along the edges of pour forms

There were no temporary vertical structures necessary to support the metal deck plates and the weight of the concrete. Figure 13(a) and 13(b) illustrates that all of the necessary reinforcing steel was installed for the slabs and composite columns as well. The lines for equipment were also placed in this stage. The vertical column steel reinforcement was continued down below the pour forms of the

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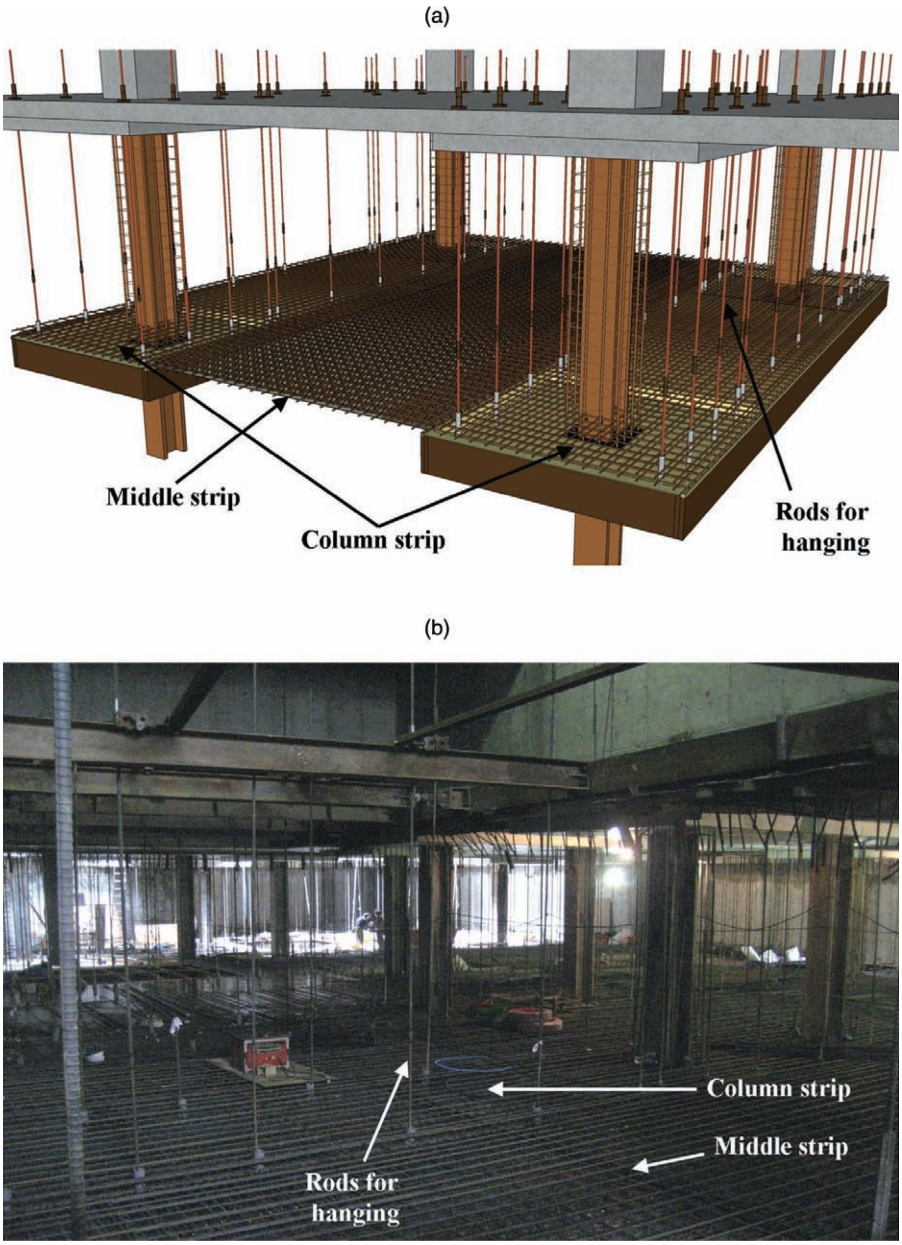

Figure 13. Placement of rebar. (a)–(b) Two-way placement of rebar

slabs to provide monolithic behaviour. The pour forms for the column were also prepared to form composite columns.

Finally, concrete was poured for slabs in Figure 14(a) and cured in Figure 14(b), in which hanging steel rods for the next floor are shown. All of the steel rods were carefully removed in an alternating

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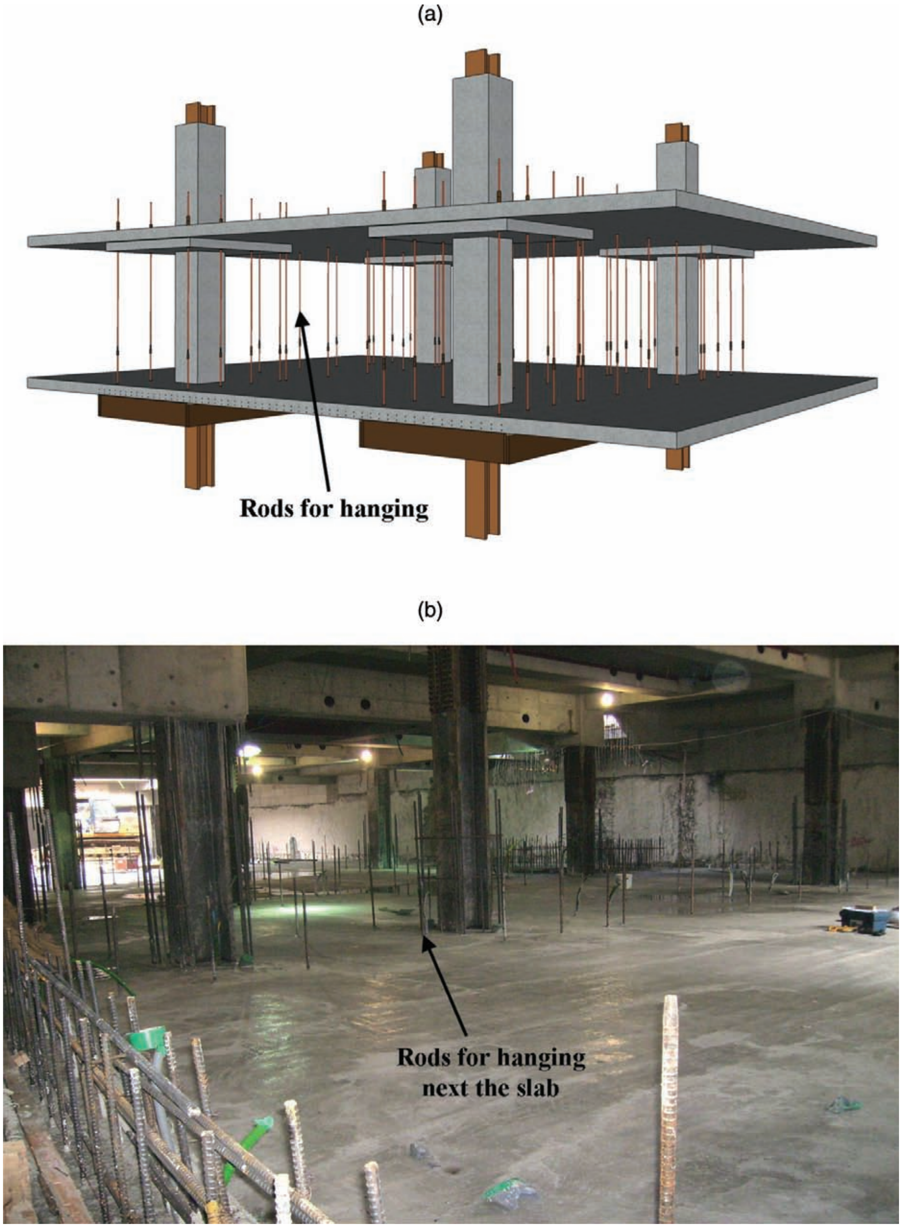

Figure 14. (a) Concrete cast for slab. (b) Cured concrete slab surface

manner from the slab above after 15 days. Then, after they were fastened again at the floor, just cured, Figure 14(b) became identical to Figure 7(a) and 7(b).

After this stage, six rods were connected to the chain of the electric crane for lowering. The rest of the fasteners were released and descended. Excavation was carried out regardless of the site concrete work going on at any time during the construction.

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5. POUR FORM DETAILS

5.1 Steel frames for pour forms

The GFRP was used, in Figure 16, as the flat surface of the pour forms to make the removal of the form from the cured concrete fast and easy. The GFRP pour forms lasted until the end of the construction without major repair. These pour forms were also lighter than conventional pour forms, contributing to a reduction in the number of steel rods required. The GFRP produced not only a fast removal of the pour forms from the concrete surface but also a good quality concrete surface. The six rods lowered by the electric crane are illustrated with the other 20 disconnected rods in Figure 9(a). The platform along the edge of the pour forms is also shown. Figure 15 illustrates the steel frame assembled to enable the pour forms to resist the vertical loading, including the weight of the concrete and the construction weight. Only four people were required to remove, lower and relocate the $3{\cdot}2 \times 14{\cdot}75$ m wide pour forms. Figure 16 shows how the pour forms were fixed to the preinstalled steel columns.

5.2 Fasteners and couplers

The fasteners shown in Figure 17 consist of base plates and couplers used to tie the pour forms to the slab above. These fasteners were also used for location and adjustment of the pour forms. They locked the steel rods to the slab, holding the weight of the construction load during descending and during concrete pouring. A close view of the couplers used to connect the descended steel rods to the rods tied to the slab above, depicted in Figure 10(a) and 10(b), is shown in Figure 18. The screw thread was made to fit the outside of the steel rods.

Figure 15. Steel frame supporting pour form with rods

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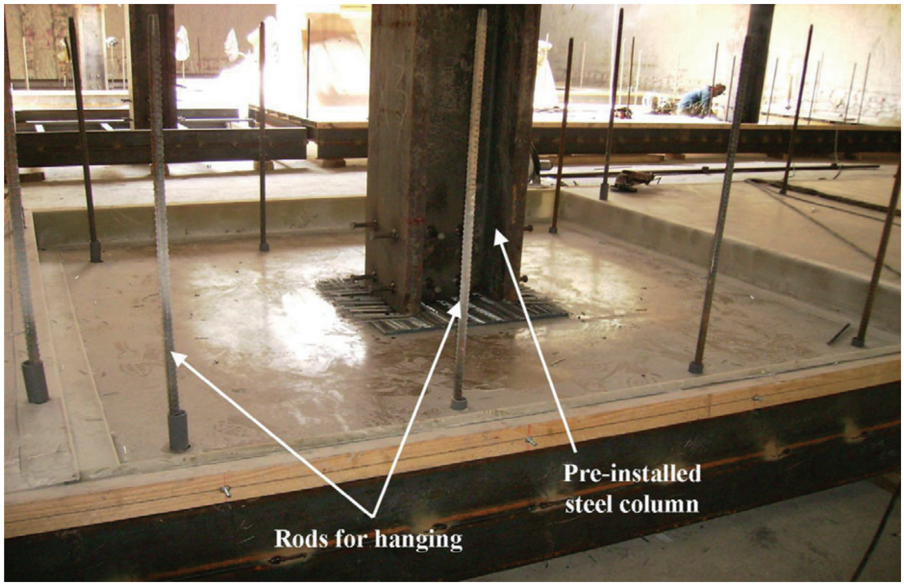

Figure 16. Surface of glass fibre-reinforced polymer pour form

Figure 17. Fasteners

6. CONSEQUENCES OF THE TECHNIQUE

This study describes how this new technique contributed to a reduction in construction costs and schedule.

As excavation began, the major floor framing structures of the ground level and slab were installed to provide both excavation support and a construction platform. The floor framing at each basement

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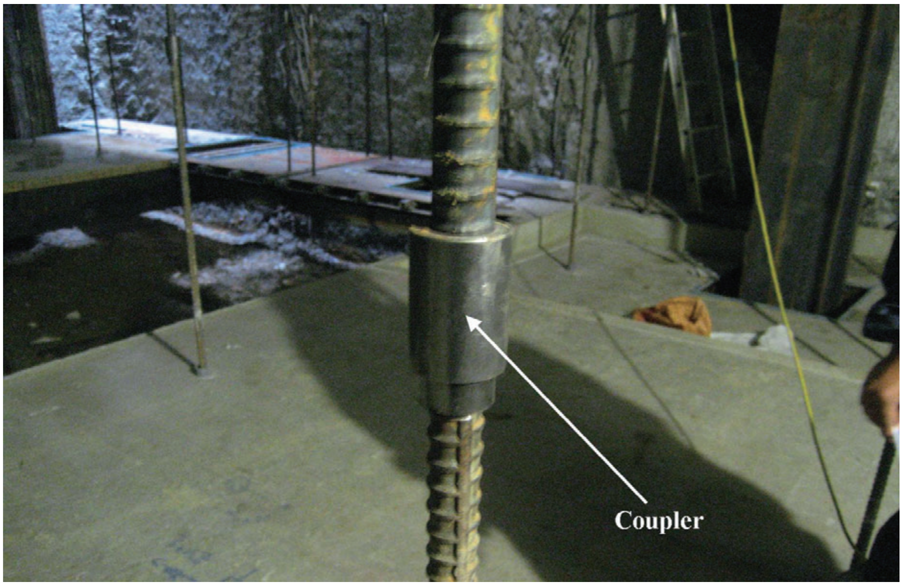

Figure 18. Couplers

level was then constructed to form a lateral load-resisting system. When the ground level was completed, simultaneous construction of the superstructure from ground level and the substructure from basement level began. This type of construction, which is termed 'top-down', utilized suspended pour forms to support the construction weight.

The flat GFRP pour forms and the metal deck plate decreased the floor height, resulting in a reduction of required soil excavation. The technique introduced in this paper presents many advantages over the conventional pour forms, which require considerable effort to detach, move to the next floor, reinstall and support. The required labour was also significantly reduced. The pour forms used in the application of this study demonstrated simple installation and removal, thanks to the GFRP material, that can be repeated for many cycles. The flat slab construction was shown to be an effective method for constructing underground structures, and has recently become a preferred construction method in Korea. The flat GFRP forms are an effective approach to use when a project involves repetitive flat floors and unit layouts typical of deep excavation-type underground structures. The GFRP form allows the construction of the flat slabs in one process, reducing the cycle time needed to construct structures.

7. CONCLUSIONS

A new concept of hanging pour forms for casting concrete by using steel rods suspended from the floor above has been pioneered in Korea. The construction was carried out with a 'top-down' approach, with steel rod hanging pour forms used for casting the concrete. The pour forms were then slid down to the next floor using an electric crane, while excavation was carried out independently of the concrete work.

This study introduced the first application of this new concept, in which flat GFRP pour forms with metal deck plates suspended by steel rods from the above floor were employed. This approach offers considerable advantages over the conventional top-down technique, including a shortened construction schedule and lowered costs.

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