Automated Construction System for High-rise Reinforced Concrete Buildings

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Abstract

The all-weather automated construction system has been developed to reduce the total cost of high-rise reinforced concrete building construction, and was applied to a 26-story reinforced concrete condominium project located in Chiba prefecture in 1995 for the first time in the world. This automated construction system consists of four major technologies: a) Synchronously climbing all-weather temporary roof; b) Parallel material delivery system with one construction lift and three overhead cranes carrying three transfer hoists; c) Prefabrication and unification of construction materials; and d) Material management system using database system linking with CAD.

Consequently this automated system is effective when used at the site. It ensures good quality, improves the working and environmental conditions, reduces the construction period, manpower, and wastes, and improves overall productivity.

1. Introduction

In Japan, the lack of and aging of skilled construction laborers have been steadily worsening. In order to solve this problem, we need to raise productivity significantly and to improve the terms of employment and working conditions to attract young laborers. Obayashi Corporation has developed a new building construction system that improves productivity greatly. The automated construction system for high-rise reinforced concrete buildings is a part of this new system.

The basic principle of this system is to integrate techniques such as all-weather, mechanization and automation, prefabrication and unification, and the use of information to build the most suitable automated system for tall reinforced concrete apartment houses that are in demand in urban regions. It is difficult to raise the level of automation for reinforced concrete structures compared with steel structures in terms of cost and effect. An all-weather assembly plant can easily be set on a steel structure using ABCS (automated building construction system, developed by Obayashi Corporation in 1989)[1], but it would be difficult to do with a reinforced concrete structure because the concrete must be left to harden.

We developed and applied an automated system aiming at CAD/CAM for complicated reinforcement work in a 41-story reinforced concrete apartment house construction from 1988 to 1990[2]. Automation at the work level (a part of the construction process) did not improve productivity sufficiently and greater automation and systematization at the project level (the whole process) were required. So we began to develop an automated construction system for high-rise reinforced concrete buildings in 1991 and as a result of feasibility studies for some proposals, we chose the optimal system for practical use in 1994 and used it to build a 26-story reinforced concrete apartment house in Tokyo Metropolitan area in 1995 for the first time in the world (Figure 1). This system is called BIG CANOPY (Big Canopy

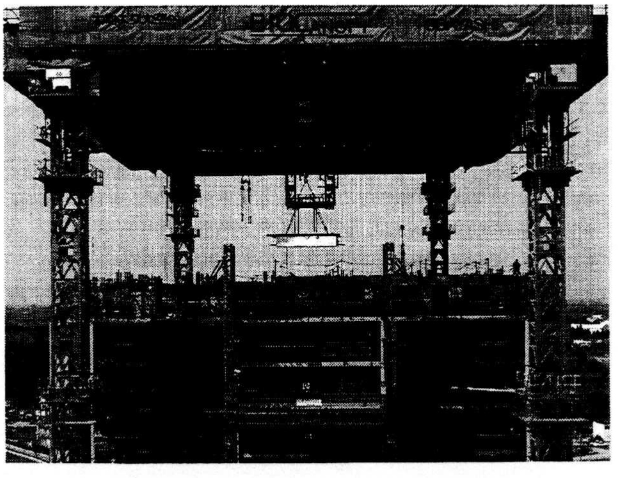

Figure 1: Whole view of BIG CANOPY

automation system for high-rise reinforced concrete buildings) and is described in the following.

2. Outline of BIG CANOPY

2.1 Main features of the system

In BIG CANOPY, we set a parallel material delivery system with automated overhead cranes and one large construction lift under an all-weather synchronously climbing temporary roof frame, and used versatile, all-round workers, extensive prefabrication and unification of construction materials, and a material management system using a database linked with the CAD system. The main features are as follows:

(1) Improvement of productivity: The overhead crane is superior in operability compared with the tower crane, and the parallel delivery system increases the efficiency of delivery and erection, and versatile workers can cooperate without wasting time.

(2) Stability of quality: Quality is stabilized by prefabrication and unification, and the all-weather temporary roof.

(3) Short construction period: The period is shortened by the use of prefabrication and unification, stable processing by all-weather construction, and early commencement of the interior finishing work.

(4) High degree of design freedom: As temporary posts are independent of the building, we can flexibly apply the system to various building shapes. According to some statistical data, this system can be applied to about 80% of high-rise reinforced concrete buildings.

(5) Improvement of construction environment: Severe heat, wind and rain are moderated, and workers can work safely and comfortably under the temporary roof.

(6) Safety to perimeter: The area of activity is compact, and safety of the neighborhood is high.

(7) Reduction of debris: Prefabrication and unification reduce debris.

(8) Reduction of total cost: The above (1)~(7) reduce overall cost.

2.2 Synchronously climbing temporary roof

The synchronously climbing temporary roof consists of four tower crane posts erected independently outside of the building, climbing equipment, and temporary roof frame. We developed a new synchronously climbing jack system to keep the roof level when moving up and down. Figure 2 shows the control monitor.The roof is raised two floors at a time. The up and down movement speed of equipment is 300 mm/min, and each 6-m climb takes slightly less than one hour.

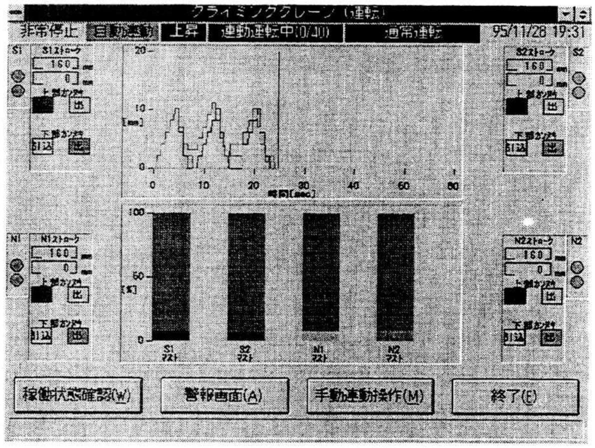

Figure 2: Control monitor of synchronously climbing equipment

The temporary roof is a shingle roof with folded thin steel plates on a steel frame truss structure and is about 50 m square. The entire weight including the roof frame, climbing equipment, overhead cranes and jib-crane is about 600 t. The jib-crane set on the temporary roof was used for adding posts after climbing and for dismantling the temporary roof frame.

2.3 Parallel delivery system

The parallel delivery system consists of a construction lift and three overhead cranes (Figure 3). The central overhead crane (delivery crane) removes a load from the lift and the right or left crane (erection crane) receives the hoist with a load from the delivery crane and erects it. These machinery reduce the waiting time of both workers and machines, and achieve efficient delivery and erection by simultaneous operation.

Before deciding the specifications of the parallel delivery system, we examined the cycle time of each precast concrete (PC) member erection and line balance of a lift and cranes by using a simulator on a personal computer (Figure4).

Hoist exchange between the delivery crane and erection crane is performed as shown in Figure 5. This system is mostly manual, but the traveling of the delivery crane and crane girder positioning between the delivery crane and erection crane are automated to reduce the work load on the operator. We introduced a suspender device to control load rotation by gyroscopic moment to prevent

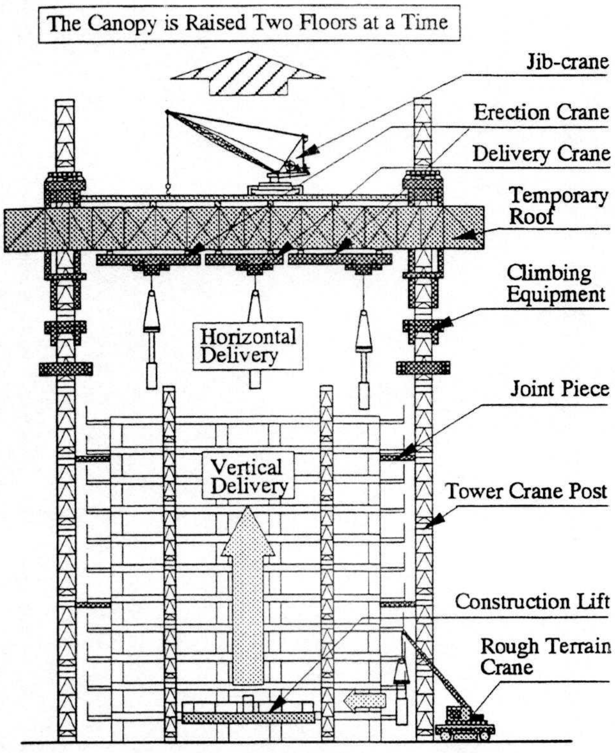

Figure 3: Parallel delivery system

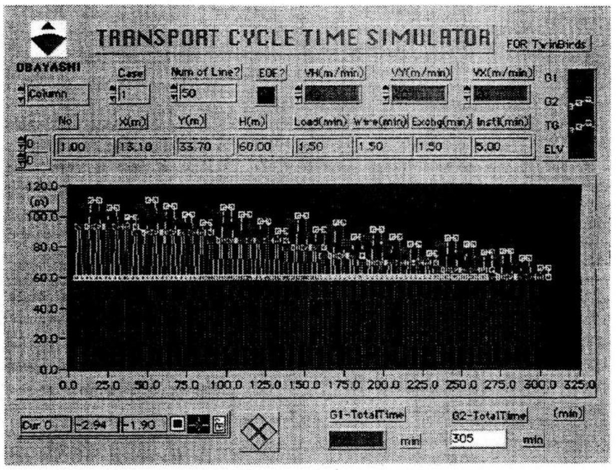

Figure 4: Transport cycle time simulator

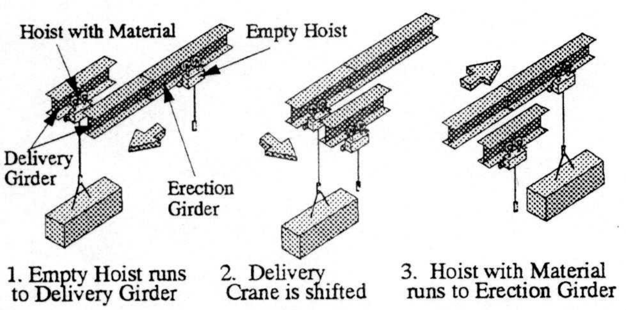

Figure 5: Hoist exchange system

Table 1: Specifications of parallel delivery system

Name and Number of Device		Specification
Construction Lift	1	Loading Capacity :6t Winching up Speed :40m/min Control Type:Invertor
Hoist Exchanging Overhead Crane		Operation Type :Manual/Automatic Wireless Remote Control Control Type :Invertor
Delivery Crane	1	Maximum Traveling Speed :40m/min Suspended Capacity :7.5t
Erection Crane	2	Maximum Traveling Speed :30m/min Suspended Capacity :7.5t
Electric Hoist	3	Maximum Traversing Speed :33m/min Suspended Capacity :7.5t
Jyroscopic Suspender	3	Operation Type :Wireless Remote Control Weight:1100kg Rotating Drive:Jyroscopic Moment Inertia Moment of Load:25ton m ^{2}

interference during hoist exchange. The major specifications of the parallel delivery system are shown in Table 1.

Members are delivered in the following order from ground to erection location.

(1) The rough terrain crane discharges members carried to the site and loads them onto the lift.
(2) The lift conveys them to the erection floor.
(3) The delivery crane removes them from the lift.
(4) The delivery crane runs to the waiting erection crane and stops at the correct position.
(5) The exchange of hoists is done between the delivery crane and erection crane. Then the delivery crane runs back to the lift top and the loaded hoist traverses to the erection point.

2.4 Material management system

The concept of the material management system is shown in Figure 6. The material management database which links up with CAD shop drawings is used to rationalize the planning from material delivery to erection and the actual management. The material management is unified by using bar codes attached to the materials at the factory. Figure 7 shows a worker reading the bar code of a girder by using a portable terminal. A screen display used to monitor the state of progress of PC member erection is shown in Figure 8. The manager is able to accomplish various kinds of material management effectively by utilizing CAD.

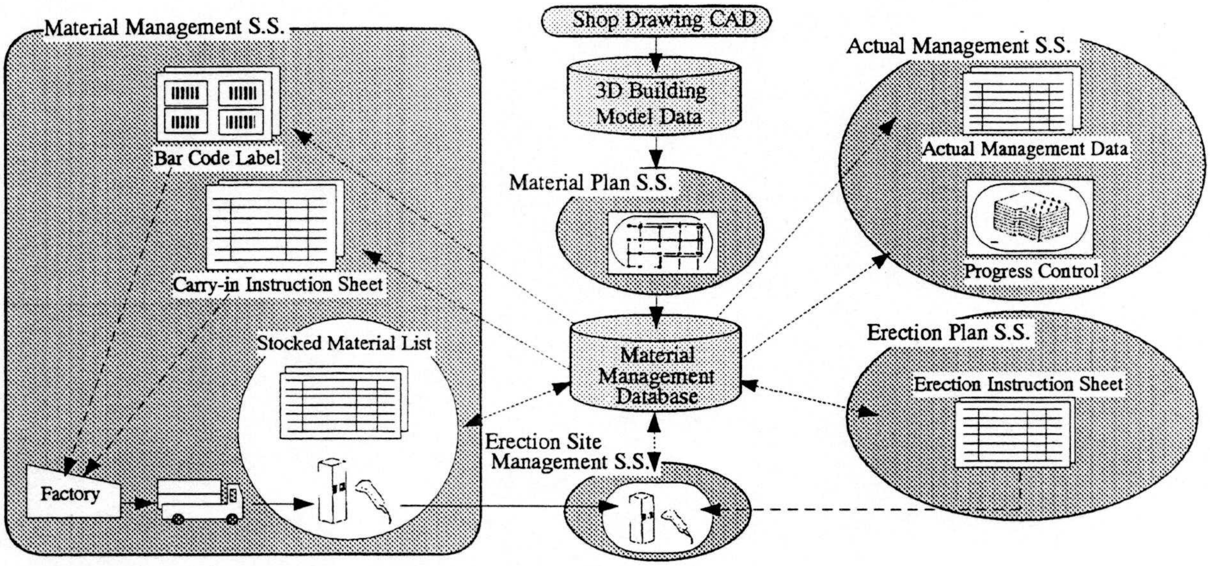

Figure 6: Material management system

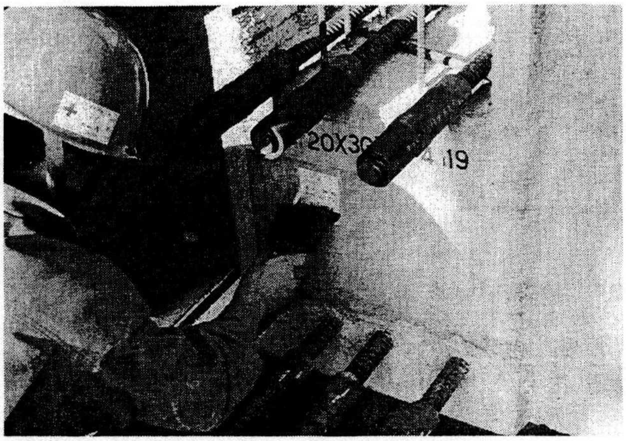

Figure 7: Reading a bar code

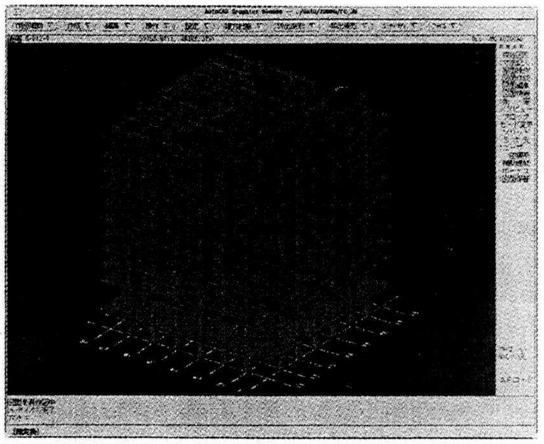

Figure 8: Progress control of PC member erection

3. Outline of construction

3.1 Outline of the construction site

The construction site to which BIG CANOPY was applied, consists of a 26-story apartment house, 2-story parking space and 2-story shopping center. The basic floor plan of the apartment house is 35 m x 34 m with an open ceiling in the center, and there is an open corridor along the void. The construction area of the basic floor is about 1,200m^2.

The number of materials per floor lifted by the parallel delivery system is about 320 PC members and about 420 items including finishing and equipment materials. Heavy finishing materials such as external wall panels and boundary wall members are lifted beforehand. Materials except these are lifted by two temporary elevators set along the open corridor.

A constant number of versatile workers is used for many kinds of works related to the skeleton, finishing and equipment of the erection floor every day.

3.2 Prefabrication and unification

We adopted the industrialized construction method using many PC members higher than the third floor, the cross section of the skeleton of which was standardized. Column, wall and balcony are full PC members, and girder and slab are half PC members (Figure 9). Concrete was placed in panel zones and the upper part of girders and slabs at the site. The rate of prefabrication was 71% of concrete volume, 97% of form area, and 79% of bar weight, which are extremely high ratios. We adopted grout

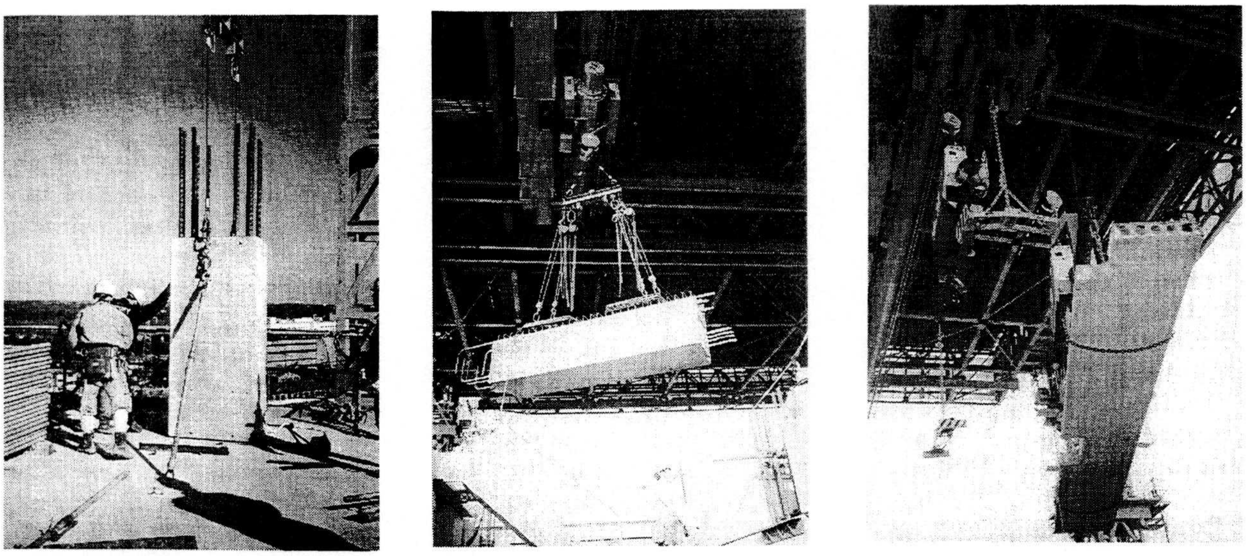

Figure 9: Erection PC members

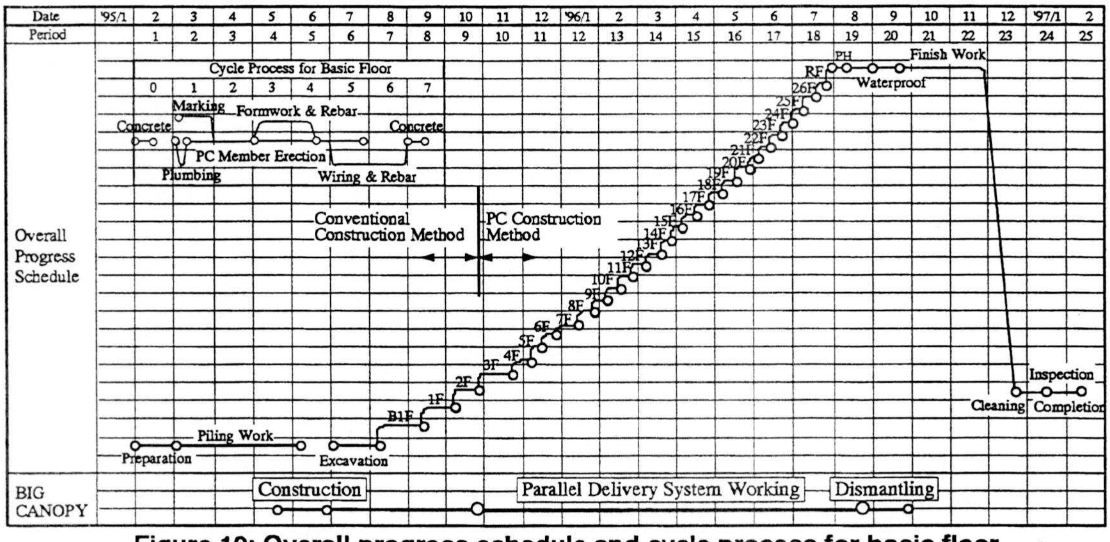

Figure 10: Overall progress schedule and cycle process for basic floor

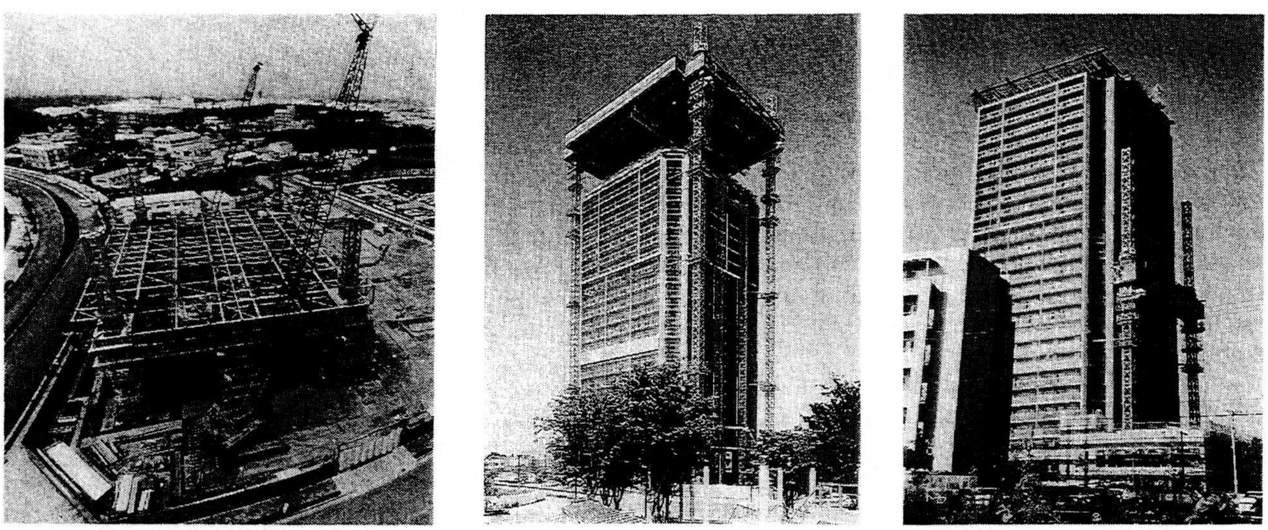

Figure 11: From construction of temporary roof to dismantling it

connection through sleeves in jointing column bars and joined screw bars with a coupler in panel zones in connecting girders.

As for the finishing and equipment work, we unified the pipes around the meter boxes, vertical drainpipes, indoor low current cables and low current main line cables; prefabricated the horizontal drainpipes and air conditioning ducts of each apartment; and precut the ALC panels, boundary wall panels and wooden axis partition to save manpower and reduce waste. In particular, we set vertical drainpipes simultaneously with the skeleton work to plug the holes in the construction floor and prevent water flow.

3.3 Construction process

The overall progress schedule with the cycle process of the basic floor is shown in Figure 10. The progress from construction of the temporary roof to dismantling it is shown in Figure 11.

Construction of the temporary roof took about one month, in May, 1995, after piling work, and then basement excavation work was done under the roof. Overhead cranes were installed simultaneously with construction of the first floor using the conventional method, and the whole system began to work from the end of October, 1995 when the PC construction method started. From August, 1996 when the skeleton work was completed, we lowered the temporary roof on the building roof and dismantled the central part with a jib-crane, took down the perimeter part by reversing the sequence of climbing, and dismantled it on the ground.

The cycle time of the basic floor was seven days and the shortest was six days. In winter when concrete was slow to harden, it took eight days.

4. Effect of applying BIG CANOPY

4.1 Improvement of work environment

Figure 12 shows measurements of the surface temperature of workers' clothes and material (steel bars) under the temporary roof and outdoors in fine weather in the summer. There were differences of about 10°C maximum with workers' clothes and about 25°C maximum with bars between under the temporary roof and outside.

In outdoor work, workers' measured heart-rate was 134 beats/min at maximum with a mean value of 103 beats/min, and was about 80% and 40% higher compared with that at rest measured in the lunch break. On the other hand, when working under the temporary roof, the heart-rate was 108 beats/min at maximum with a mean value 89 beats/min, and was about 45% and 20% higher compared with that at rest. The temporary roof thus significantly reduced the physical load on workers. A questionnaire survey showed strong approval of the temporary roof; work efficiency deteriorates as temperature rises when working in a hot environment.

There were 66 days when the temperature during activity time exceeded 30°C of the 123 days from July to September in 1995 and in July, 1996. The decline of productivity is equivalent to 50 hours (6.3 days) of lost time[3]. It is thought that there is about a 10% reduction in productivity in the hot summer, but under the temporary roof there was almost no degradation of work efficiency.

The effect of wind velocity during the PC construction period (from November, 1995 to July, 1996) is shown in Figure 13. The total time when the mean wind velocity exceeded 10 m/sec on the roof during activity time was 87 hours, hence there

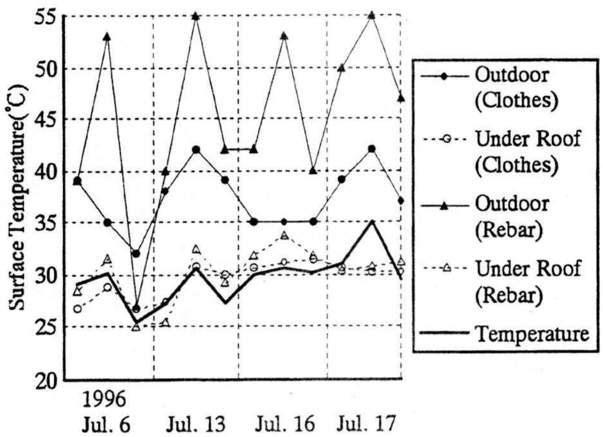

Figure 12: Surface temperature of workers' clothes and steel bar

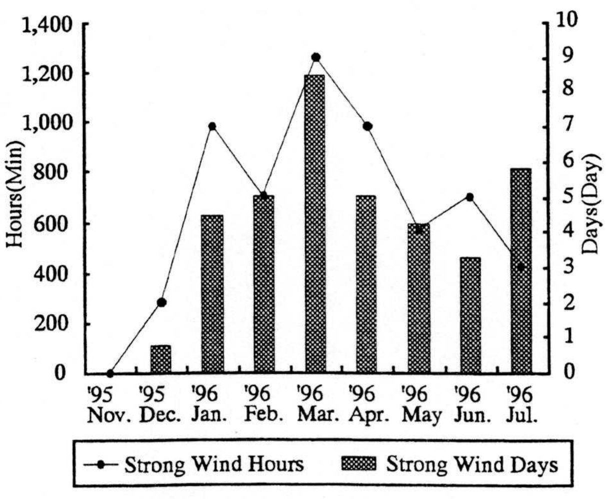

Figure 13: Strong wind effect

were about 12 days when tower crane work was impossible, but only 1.5 days were interrupted in this system. The cause is thought to be as follows: the wind velocity is reduced to around 2/3 under the temporary roof; vertical delivery is done by the lift; and as the wire length was short, load swing caused by the wind is small.

4.2 Improvement of productivity

At first two tower cranes (200tm) were planned to be used in this construction. Using the results of work measurement, we compared the erection time of PC members and found that the capability of the parallel delivery system is equal to about 2.5 tower cranes (Figure 14). Efficiency is improved because: the parallel delivery system is effective; overhead cranes are little affected by wind; and the operator can operate the crane while grasping the erection situation precisely.

The analysis of the learning effect for each activity is shown in Figure 15 and 16.The learning rate of total activity is about 87% and there are some activities less than 85%, so the learning effect was high. The total number of laborers on the fourth floor at the beginning was many, but that on the 25th floor was reduced to 36%.

Labor productivity of skeleton work is compared among four kinds of construction methods for high-rise buildings in Figure 17. The four kinds of construction method are: a) the conventional method of construction, b) system form method of construction in which PC slabs are used, c)construction method using PC members with tower crane, and d) BIG CANOPY. The number of workers engaged in skeleton work of BIG CANOPY was about 25% of the conventional method of construction, about 35% of the system form method of construction and about 65% of the PC method of construction. Labor is saved by the simplification and standardization of work by prefabrication, and the reduction of waiting time by the effective delivery system and use of versatile workers.

We did not use the complete automated erection system of ABCS due to cost and effect. This time we automated only exchanging of the hoist for the overhead crane. We conducted an experiment to widen the scope of automation, with the delivery crane removing the load from the lift, moving to the erection crane with a loaded hoist, and returning to the lift top after exchanging hoists (Figure 18). As a result, the time of one cycle of automatic control was about 5% more than that of manual control, but we could reduce one operator. Complete automation is technically possible if we combine this upgraded system with the material management

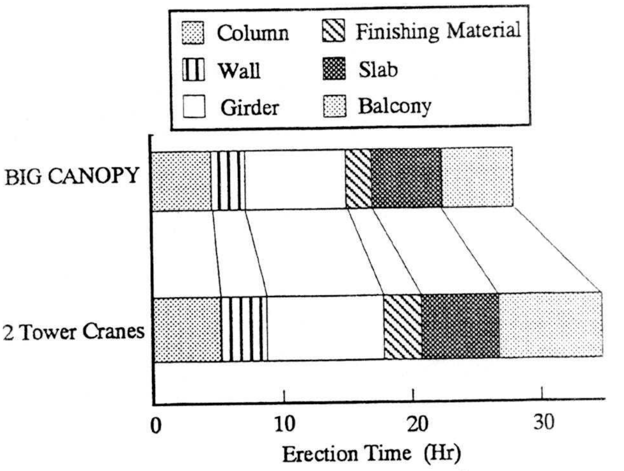

Figure 14: Efficiency comparison between two tower cranes and parallel delivery system

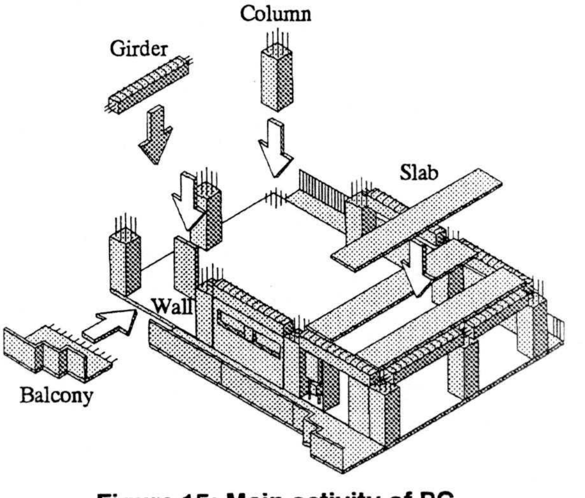

Figure 15: Main activity of PC construction

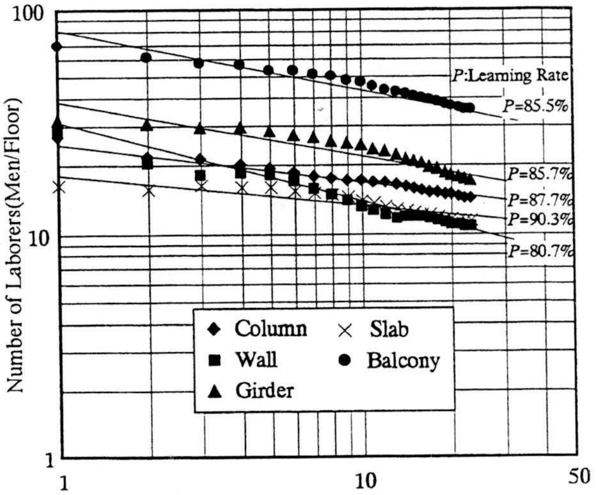

Figure 16: Learning effect

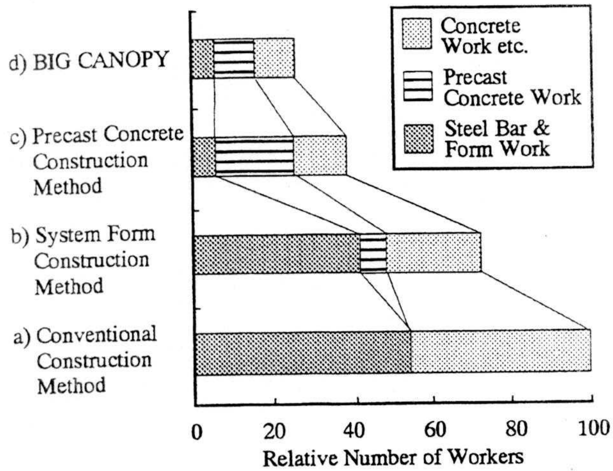

Figure 17: Productivity comparison among four construction methods

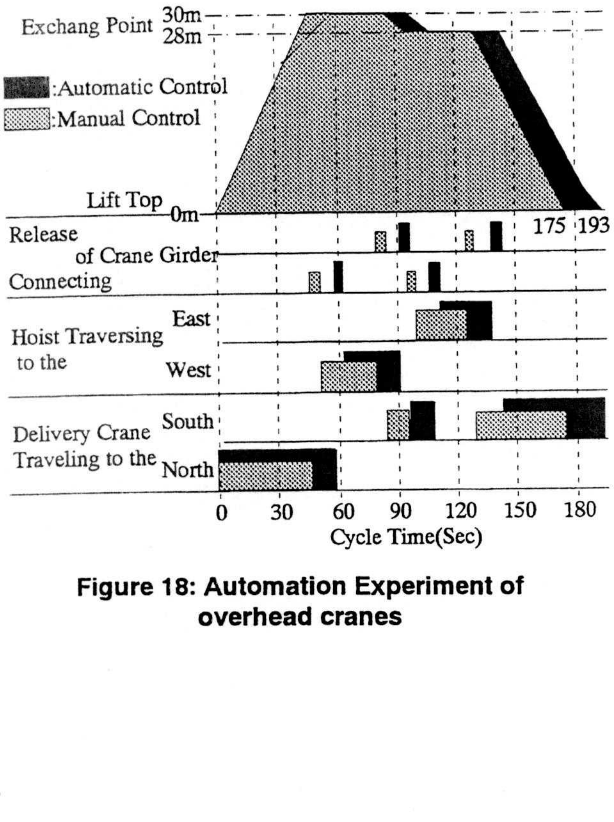

Figure 18: Automation Experiment of overhead cranes

system using bar codes.

4.3 Shortening of construction period

Skeleton work was interrupted by one month to erect the temporary roof, but there was no interruption of activity by weather. As the temporary roof stabilized the skeleton work and allowed the finishing work to start early, the expected construction period for works by two tower cranes (28 months) was reduced by four months.

5. Conclusion

BIG CANOPY is used mainly for the construction of high-rise reinforced concrete apartment buildings. However, there is the constraint that temporary construction costs must not increase greatly because of the low construction unit cost of reinforced concrete buildings. Accordingly, in our development we utilized the construction equipment that we possessed and reduced the development cost by using general-purpose equipment in the market as much as possible. We chose the optimal automation level of the system so that workers could use their skills, and examined the balance of cost and effect. We achieved very high productivity and reduced the construction period without increasing construction cost. This system increases the level of automation, adds a new function and is flexible according to the situation. BIG CANOPY is thus viable and has a bright future.

Acknowledgment

Finally, we express our gratitude to the members who cooperated with the development of this system. Gratitude is also expressed to Minoru Yosida, general manager and the members of the construction site office.

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