PRESENT CIRCUMSTANCES OF AN AUTOMATED CONSTRUCTION SYSTEM FOR HIGH-RISE REINFORCED CONCRETE BUILDINGS

Noriyuki Furuya [a], Takashi Shiokawa [a], Koji Hamada [a], Kohei Kurita [a], Isamu Kunimoto [b] and Hiroshi Miyakawa [b]

[a] *Obayashi Co., Technical Research Institute, Japan*
[b] *Obayashi Co., Building Construction Division, Japan*
n.furuya@tri.obayashi.co.jp

Abstract: An automated construction system has been developed to reduce the total cost of high-rise reinforced concrete building construction. It has been already applied to three condominium construction projects in Japan and one office building construction project in Singapore since 1995. Application of this system ensures good quality, improves the working and environmental conditions, reduces the construction period, manpower, and wastage, and improves overall productivity. Through these applications, the authors have improved and adapted the system to suit various conditions.

Keywords: automated construction, all weather, industrialized construction method, parallel delivery, material management.

1. INTRODUCTION

The construction industry in Japan faces serious problems of a shortage of skilled construction workers, and lower productivity compared to other industries.

In 1995, Obayashi Corporation developed the world’s first automated construction system (called “Big Canopy”) for high-rise reinforced concrete buildings [1].

The system is designed to stabilize the construction process and the quality under a suitably automated, comfortable working environment, to greatly increase the productivity, to shorten the construction period, and to reduce the total construction cost. This paper outlines Big Canopy, the results of using the system on four projects to date, and how the system has been improved according to building conditions.

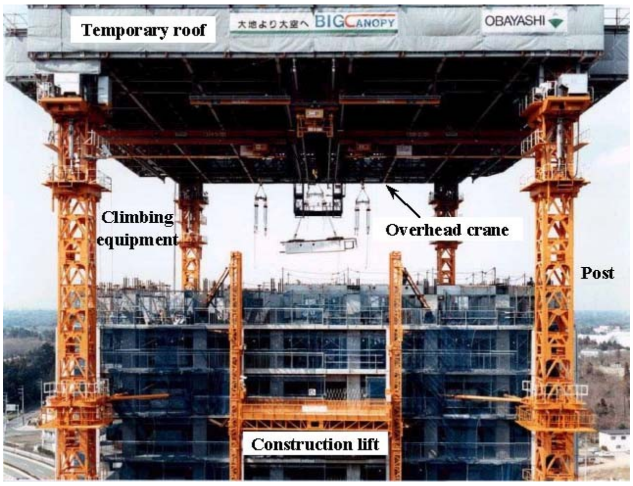
2. OUTLINE AND APPLICATION OF SYSTEM

Big Canopy consists of the four major elements: a) a synchronously climbing all-weather temporary roof; b) a parallel material delivery system which is composed of a construction lift and overhead cranes; c) prefabrication and unification of construction materials; and d) a material management system.

Photo. 1 shows the whole view of Big Canopy first applied.

Table 1 shows the outline of construction projects to which Big Canopy has been applied. After applying the initially-developed system (called “type A” in the table) to a high-rise apartment house (project Y) in 1995, it was adapted for a high-rise apartment house (project K), and a high-rise office building in Singapore (project D). The newly developed system (called “type B”) was then used for construction of a high-rise apartment house (project H). Type A and type B differ in terms of the equipment used for the parallel delivery system.

The appearances of Big Canopy applied to project K, H and D are shown in Photo. 2~4.



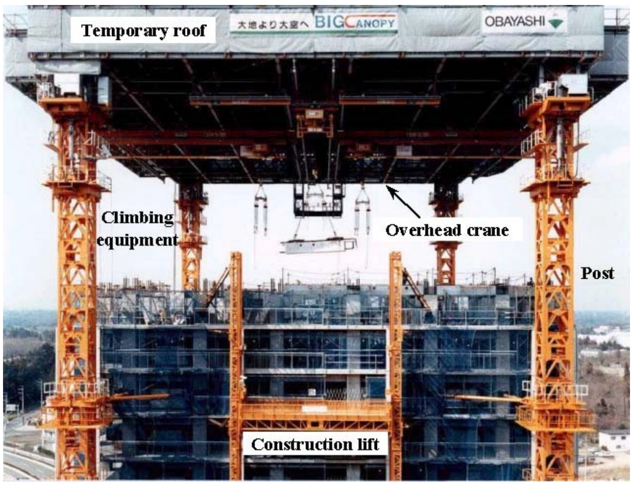


Photo. 1 Whole view of Big Canopy

2.1 Outline of project Y

The building is a 26-story apartment house having a frame structure and typical floor dimensions of 34.9 m × 33.7 m. The industrialized construction method using PC members was used for the upper part from the third floor.

The temporary roof was assembled after the piling work. The roof dimensions were 41.7 m × 49.0 m. Then the excavation work for the basement and the construction work up to the second floor were done by the conventional construction method under the roof.

Three overhead cranes were installed at the bottom of the temporary roof.

2.2 Outline of project K

The building is a 20-story apartment house having a frame structure and typical floor dimensions of 25.2 m × 25.2 m. The PC construction method was used for the upper part from the second floor.

The temporary roof dimensions were 35.5 m × 43.4 m, and the structural components of the roof used in project Y were partially cut and adapted. The roof was assembled on the slab of the second floor.

2.3 Outline of project H

The building is a 33-story apartment house having a frame structure and typical floor dimensions of 30 m × 30 m. The building has setbacks in the four corners at the high-rise part. The PC construction method was used for the upper part from the third floor.

The temporary roof dimensions were 37.7 m × 46 m. The roof was assembled on the second floor.

2.4 Outline of Project D

The building is a 28-story office building in Singapore having typical floor dimensions of 37.9 m × 46.8 m. The building has a frame structure for the perimeter part and a wall structure for the core part. The industrialized construction method using PC members was used for the upper part from the second floor.

The roof was assembled on the second floor. The roof dimensions were 41.7 m × 60.0 m. When it was adapted from project K, the roof span was extended.

Since there was almost no space at the site, it was impossible to set up a stockyard for PC members. Furthermore, there were the following severe restrictions unlike for the previous apartment house projects in Japan:

1) The dimensions and weight of PC members were large.
2) It was difficult to use the construction lift by standing perpendicular members such as columns and walls on the loading platform, because the PC members were tall.
3) The central overhead crane was in heavy use

Table. 1 Profile of four projects

	Project-Y	Project-K	Project-H	Project-D
Location	Yachiyo, Japan	Fukuoka, Japan	Kobe, Japan	Singapore
Building use	Apartment House	Apartment House	Apartment House	Office Building
Structure	RC,B1F/26F/PH1F	RC,20F/PH2F	RC,B1F/33F/PH4F	RC,28F/PH2F
Total Floor Area	25,540m^2	12,641 m^2	30,433 m^2	42,652 m^2
Building Height	91 m	69 m	114 m	138 m
Construction Period	Jan.1995~Feb.1997	Sep.1996~Mar.1998	Apr.1997~Jun.1999	Nov.1997~Sep.1999
Temporary Roof Area	1,980 m^2	1,330m^2	1,590 m^2	2,490 m^2
Delivery System type	Type A	Type A	Type B	Type A

Photo. 2 Project K


Photo. 3 Project H

Photo. 4 Project D

compared with the right and left crane, because many PC members are concentrated in the center of the building.

4) In order to attach the safety net on the PC beam, and to raise the perpendicular members such as columns and walls which were placed horizontally on the lift and conveyed, these members had to be first taken down to floor under construction.

3. IMPROVEMENTS AND NEW DEVELOPMENTS

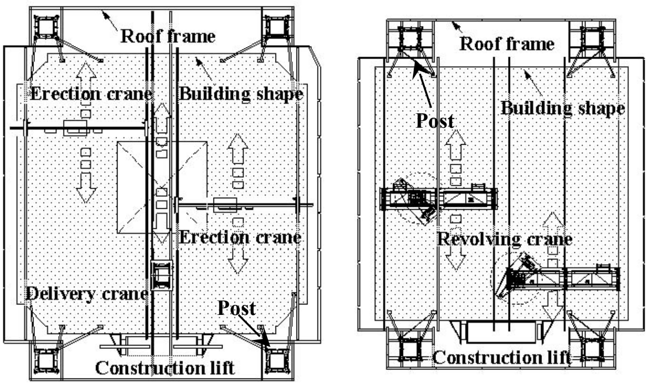
3.1 Improvement of the synchronously climbing all-weather temporary roof

3.1.1 Labor-saving of assembling and dismantling work of the temporary roof

Compared with ordinary roof frames, project Y required much time and labor for assembling and dismantling the temporary roof frame. Therefore, the roof frame was unified more and assembling work was performed on top of the slab of the building under construction.

3.1.2 Countermeasures for building with setback

When a building has setback at a corner, it is difficult to attach joint pieces between the temporary roof posts and the building, so a temporary steel column and beam skeleton was erected into the setback part, then the joint pieces were attached to this skeleton. The temporary skeleton was erected without modifying the construction cycle process.



Type A   Type B

Fig. 1 Arrangements of both types of crane

3.2 Improvement of parallel delivery system

3.2.1 Development of overhead crane with revolving boom

The original overhead cranes consisted of three traveling girders, and three hoists that can transfer among these girders. The central overhead crane (called a delivery crane) picks up members from the construction lift, and delivers them to the right or left cranes (called erection cranes). Both erection cranes receive members from the delivery crane by hoist exchange and deliver them to the erection places.

In project H, two overhead cranes having a revolving boom with a radius of 3 meters were newly developed (Photo. 5). These cranes can pick up members from the lift and deliver them without transfer by hoist to the erection place.

The arrangements of both types of crane are shown in Fig.1.

3.2.2 Development of rack-and-pinion construction lift

The original construction lift was driven by a winding wire and winch. When a post was added to the top, wiring work was necessary.

In project H, a rack-and-pinion type of construction lift was newly developed (Photo. 6). Servomotors spin the pinions installed in both sides of the loading platform, and the loading platform is moved up and down by gearing with the rack of the posts. Since the rack and the power-feeding trolley are installed in the post, wiring work is unnecessary.

Moreover, in order to increase the efficiency of delivery, a pit was established at the center of the loading platform so that concrete buckets, PC column members and so forth can be inserted easily, and the speed of rise and fall could be increased.

3.3 Improvement of material management system

In project Y, although an EWS (engineering workstation) based material management system was

Photo. 5 Overhead crane with revolving boom

Photo. 6 Rack-and-pinion type construction lift

employed, it was subsequently modified to run on a personal computer. As a result, result data could easily be processed by general-purpose software, thus reducing the work for the person in charge.

4. EVALUATION OF PARALLEL DELIVERY SYSTEM

4.1 Calculation of cycle time

The working time of each equipment of the parallel delivery system can be expressed as the sum of a series of working times as shown by Eq. (1).

As the working story becomes high, the cycle time [$_{L}T_{cycle}$] of the construction lift increases. On the other hand, the erection time [$T_{erection}$] of PC members decreases gradually as workers become more skilled, as expressed by Eq. (4). The working time of each type of overhead crane [$_{C}T_{cycle}$] depends on the mechanical specifications and the kind of member to be delivered.

To allow two or more equipments to interlock in the case of the parallel delivery system, the efficiency of the system itself is determined by the minimum capacity of all the equipment as given by Eq. (2).

On the other hand, the cycle time of a tower crane [$_{TC}T_{cycle}$] does not depend on the number of cranes used, but is constant as shown by Eq. (3).

Cycle time of the construction lift: [$_{L}T_{cycle}$]=[$_{L}T_{stow}$]+[$_{L}T_{rise}$]+[$_{L}T_{bundle}$]+[$_{L}T_{descend}$]
Cycle time of the delivery overhead crane of type A: [$_{DC}T_{cycle}$]=[$_{DC}T_{bundle}$]+[$_{DC}T_{wind-up/travel}$]+[$_{DC}T_{transfer}$]+[$_{DC}T_{travel/wind-down}$]
Cycle time of the erection overhead crane of type A: (1) [$_{EC}T_{cycle}$]=[$_{EC}T_{transfer}$]+[$_{EC}T_{travel}$]+[$_{EC}T_{erect}$]+[$_{EC}T_{travel}$]
Cycle time of the revolving overhead crane of type B: [$_{RC}T_{cycle}$]=[$_{RC}T_{bundle}$]+[$_{RC}T_{wind-up}$]+[$_{RC}T_{travel/revolve}$] + [$_{RC}T_{erect}$]+[$_{RC}T_{travel/revolve}$]+[$_{RC}T_{wind-down}$]
Cycle time of the parallel delivery system of type A: [$_{PA}T_{cycle}$]=max{[$_{L}T_{cycle}$], [$_{DC}T_{cycle}$], [$_{EC}T_{cycle}$]/2}
Cycle time of the parallel delivery system of type B: (2) [$_{PB}T_{cycle}$]=max.{[$_{L}T_{cycle}$], [$_{RC}T_{cycle}$]/2}
Cycle time of the tower crane: [$_{TC}T_{cycle}$]=[$_{TC}T_{bundle}$]+[$_{TC}T_{wind-up}$]+[$_{TC}T_{revolve/hoist}$]+[$_{TC}T_{erect}$]+[$_{TC}T_{revolve/hoist}$]+[$_{TC}T_{wind-down}$] - - - - -(3)
Erection time of a member: [$T_{erection}$]=$t_1 * x^{-n}$ - - - - - - - - - -(4)
Learning rate in the erecting work: P(%)=$(1/2)^n$ 7100 - - - - -(5)
Subscripts express the equipment and the work content. [t_1] is the first erection time. [x] is the repetition frequency. [n] is the learning coefficient.

4.2 Assumed cycle time, and prior evaluation of system efficiency

Fig. 2 shows the relation between the cycle time and the working height, in the case of using two types of parallel delivery system and two tower cranes. This figure assumes that each lift type has the same capacity, and that the first erection time [t_1] is 5 and 10 minutes.

As a result, the following results were obtained and it was shown that the parallel delivery systems effectively shorten the construction period compared with two tower cranes.

1) Although the cycle time of the two types of parallel delivery system differs at the lower part, it will become equal when the working height exceeds a constant value.
2) When the first erection time [t_1] is longer, the cycle time of type A becomes shorter than type B at the lower part.
3) When [t_1] is longer, the cycle time of the parallel delivery system becomes shorter than two tower cranes.
4) The cycle time of the parallel delivery system becomes shorter than two tower cranes except for an especially high building.

Fig. 3 shows the actual erection cycle time of column members in projects Y and H, and the assumed value. The values are similar. Therefore, by evaluating appropriately the first erection time [t_1] and other working time, the cycle time is given with sufficient accuracy by Eq. (2).

5. APPLICATION RESULTS

5.1 Improvement of labor productivity

Fig. 4 compares the labor man-day per unit floor area of the skeleton work by Big Canopy with other

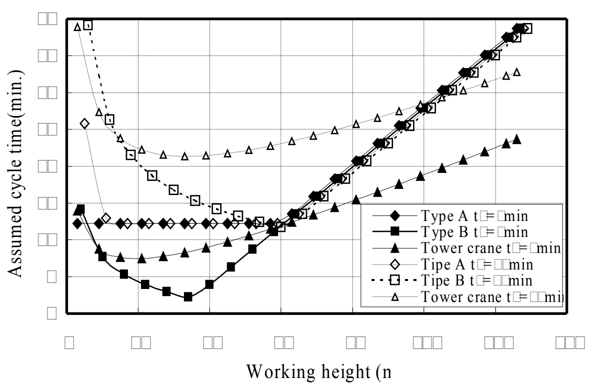


Fig. 2 Simulation for delivery cycle time

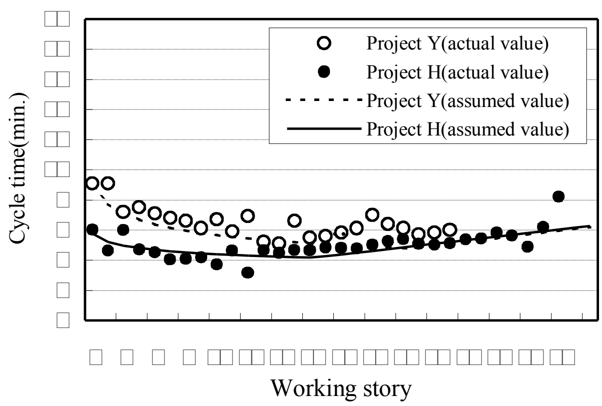


Fig. 3 Erection cycle time of column members

construction methods. The values of Big Canopy are the values of projects Y, K and H that adopted similar construction methods. When the value by the conventional construction method is set to 100, the systematized formwork construction method is 72.9, the PC construction method using two tower cranes is 38.6, and Big Canopy ranges from 20.0 to 26.0.

The productivity of project H was the highest. This is because the experience gained during projects Y and K was used effectively, and the new delivery system was more efficient. In addition, the labor productivity of project D was 23% of the conventional construction method in Singapore.

Fig. 5 shows the change for story in the mean number of cumulative labor man-days (the number of the first time is set to 100) in the skeleton work of each of the four projects. The numerical value P in the figure is the “learning rate” expressing the rate of decrease of man-days; it becomes small as the decrease in man-days becomes large.

It was the first such project and through ongoing improvement of the working procedure, the rate of decrease of man-days was large in project Y. In the subsequent projects in Japan, the rate of decrease was small because the know-how accumulated in project Y was used efficiently. Project D was the first application of Big Canopy in a foreign construction project, and also it was the first time the system was used for an office building. Although the man-days became large temporarily immediately after the start, since the floor plan was various, the rate of decrease was larger than in project Y due to the improvement in subsequent work and the value of P became the smallest.

5.2 Shortening and Stability of Cycle Time

The shortest cycle process of the skeleton work in project Y was 6 days per floor. In projects K and H, although the initial cycle process was planned to be 6 days, it helped shorten the construction period because the process was 4 or 5 days in case of the shortest term. In project D, the cycle process from the seventh floor with the standardized plan was stabilized in 6 or 7 days and the building was completed within the planned construction period.

Fig. 6 shows the change of wind velocity at the upside and downside of the temporary roof in project K when a typhoon passed near the site. Wind velocity is the maximum instantaneous wind velocity and the average wind velocity in each 10-minute period. Since the wind velocity at the downside was typically half that of the upside of the temporary roof, as shown in this figure, work was rarely interrupted by strong winds, and construction could proceed in a stable manner.

5.3 Improvement of the working environment

Outdoors, productivity falls as temperature and

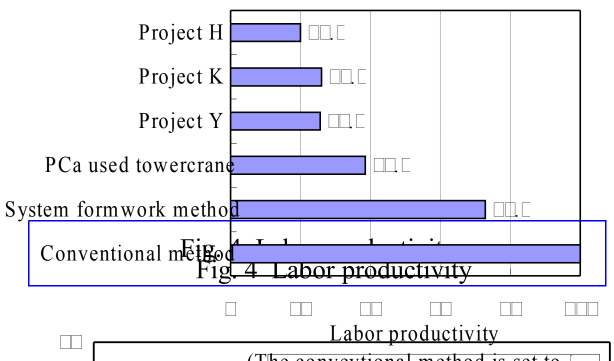


Fig. 4 Labor productivity

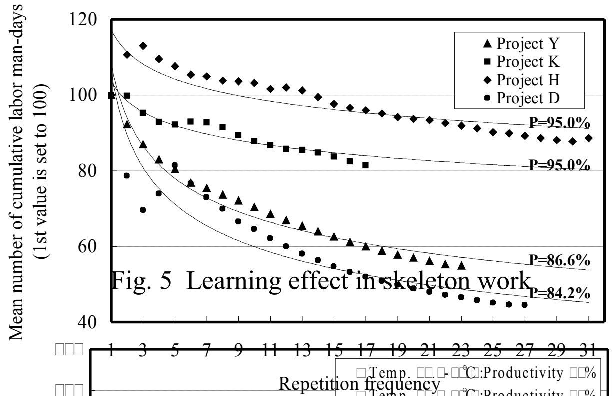


Fig. 5 Learning effect in skeleton work

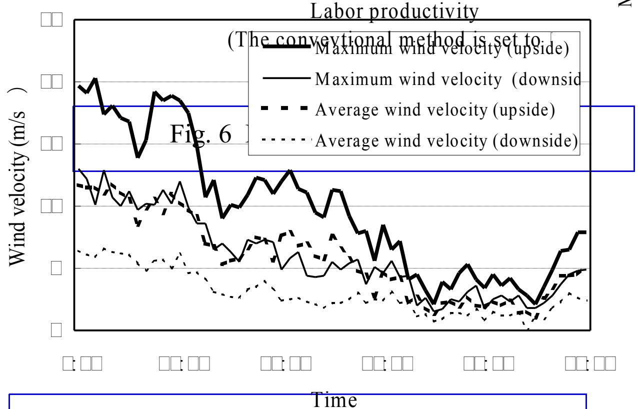


Fig. 6 Difference of wind velocity

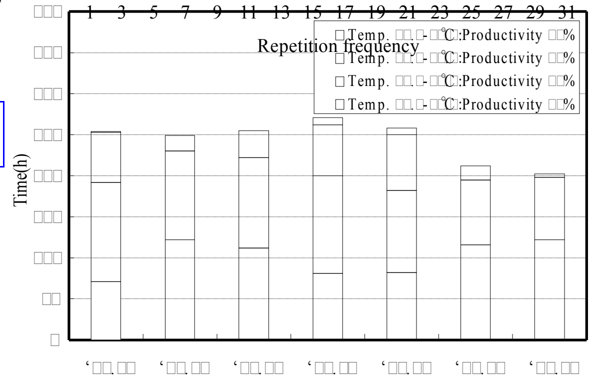


Fig. 7 Temperature division for labor productivity

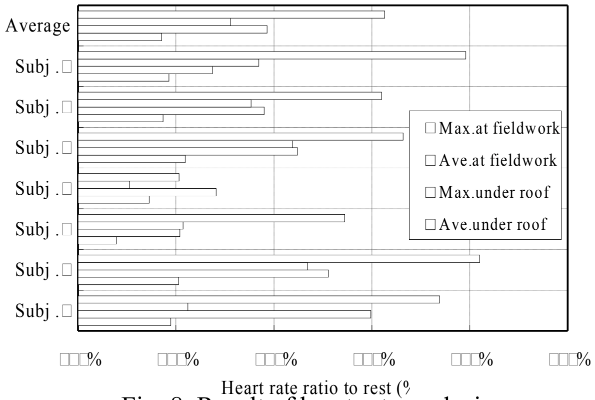


Fig. 8 Result of heart rate analysis

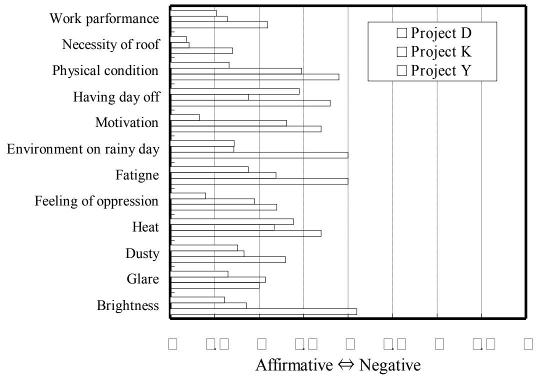


Fig. 9 Response to temporary roof

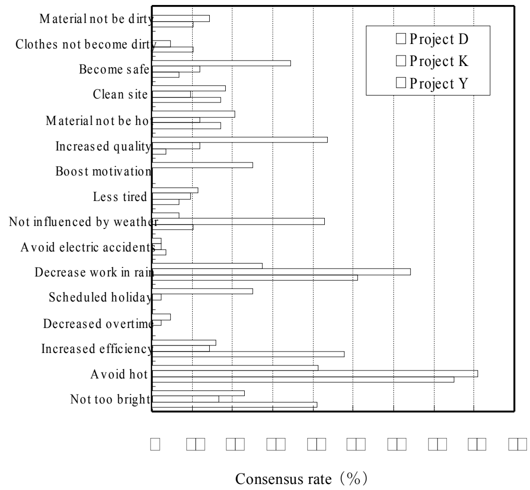


Fig. 10 Improvement of working environment

humidity rise [2]. Fig. 7 shows the monthly temperature range that is thought to have affected the productivity during construction of project D. From the figure, the total lost working time by decreased productivity is thought to be about 260 hours per year. On the other hand, the estimated lost time in Japan in 1995 which was particularly hot, was 43.3 hours per year. Therefore, the lost productivity in the outdoor environment in Singapore is estimated to be at least 6 times that in Japan. Thus, the improved work environment thanks to the temporary roof was especially beneficial in Singapore, which is very hot and humid.

Fig. 8 shows the results of a study of heart rate for seven workers carried out in Japan and Singapore under the thermal environment. The figure shows the rate of increase of heart rate compared to at rest when working under the temporary roof and in fieldwork. In the fieldwork, all subjects' highest heart rate increased by 70% on the average, and the mean heart rate was a 35% increase. On the other hand, when the working under the roof, the highest heart rate increased by 40% on the average, and the mean was only a 17% increase. Under the temporary roof, the rate of increase of a worker's heart rate is halved compared with when working outdoors, thus proving that the physical load due to temperature is reduced remarkably.

A questionnaire survey on the working environment was conducted on 119 workers. Fig.9 shows the results of responses for the temporary roof. The assessment of the temporary roof was good as a whole. In project D, the factor "Motivation" scored highly, since many people have observed the system. Fig. 10 shows the environmental factors that were considered to have been improved by the temporary roof. The factor "Avoid hot" was the most popular, and the improved thermal environment of the temporary roof was highly regarded. In project D, factors "Increased quality" or "Become safe" scored very highly compared to the results in Japan.

6. CONCLUSIONS

A new delivery system was developed and various improvements were made to the "Big Canopy" automated construction system for buildings that differed in terms of uses, dimensions, and shapes. It was shown that Big Canopy could be flexibly modified when the conditions of the building changed, and high productivity and a comfortable working environment were achieved. Future issues are to improve the delivery efficiency, and to simplify the work of assembling and dismantling the temporary roof.

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