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A Production-Installation Simulation Model of Free-Form Concrete Panels

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Abstract: Demand on free-form buildings is gradually increasing, yet owing to the difficulty of production-installation work, several problems occur in the construction phase upon construction of a building, including the increased cost and construction duration, and reduced constructibility. To solve these problems, a techonology to produce FCP using a CNC(Computerized Numeric Control) machine is developed. The technology is that the information of designed free-form buildings to the CNC machine is transferred, and the transferred information is used for RTM(Rod-Type Mold, the mold shaped by back-up rods) and PCM(Phase Change Material) shaping, and the shaped RTM and PCM have the role of molds to produce FCP. Construction duration and project cost are limited in building sites, so the efficiency of processes like production-installation of FCP for application of the technology is significant. Since it is almost impossible to change the production-installation process at the construction phase when they are established, process should be deliberately decided. Therefore, the purpose of the study is to propose a production-installation simulation model of free-form concrete panels, in aspect of PCM. This paper is establishing the process for production-installation of FCP, estimating time required by each construction type and proposing a time simulation model that changes according to various constraints based on the analyses. With the time simulation model, it will be possible to build a cost model and to review the optimal construction duration and project cost.

Keywords: Free-Form Concrete Panel, Time Simulation, Production, Installation, Phase Change Material

I. INTRODUCTION

Owing to the difficulties in production-installation of members, several problems, including cost and duration increase and reduced constructability, occur during the construction phase of free-form buildings [1-4]. To solve these problems, a technology to produce FCP using a CNC machine was developed. The technology is to transfer the information on free—form building designed to a CNC machine, to create RTM (Rod-Type Mold, the mold shaped by back-up rods) and PCM shapes using the transferred information and to produce FCP as the RTM and PCM act as forms [5]. Efficiency of the FCP production-installation process is significant to apply this technology since the space in construction sites, construction duration and project cost are limited [6]. As the construction duration is directly linked to the cost, unnecessary processes upon FCP production should be eliminated to minimize Critical Path and reduce the duration. In addition, if FCP is to be installed right after the production, no loading space is required, yet if not, a loading space is needed. Thus, the loading space should be minimized through Just-In-Time (JIT) production. Once the production-installation Process are established at the construction phase, it is nearly impossible to change them. So, careful decisions should be made on the process. Therefore, the study is intended to define the process for FCP production-installation restricted to PCM and to build a FCP production-installation simulation model that changes depending on various constraints based on the defined process.

II. PRELIMINARY STUDY

Looking into the studies related to free-form concrete production technologies, P. Mandle et al. [7] and Lindsey & Gehry[8] manufactured EPS-formwork using a CNC machine, and Toyo Ito & Associates[9] conducted a study on producing forms with wood using a CNC machine and to manufacture free-form concrete members. Franken & ABB[10] came up with free-form concrete using a digital form made of a CNC machine and acryl glass. CRAFT[11] performed studies on robot automation, construction process, new materials and computer designs for automation of free-form concrete pouring, and conducted a study on manufacturing and using machines for building automation. IMCRC[12] studied 3D printing method to make free-form concrete members. However, these previous studies only introduced the production of free-form concrete, not taking into account of constructability and the studies on production-installation for efficient arrangement of FCP in a limited construction site are required.

There were several studies, including a study on construction site layout using genetic algorithm [13-16], study on PC(Precast Concrete) yard layout [17] and study on application of 4D for dynamic site layout and management of construction project[18]. However, these studies were restricted to PC members, and there were no

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studies on production-installation of free-form members, which should be conducted.

Pheng and Chuan[19] explained just-in-time of PC components as a management tool to complement the precast concrete sector, and claimed that there are important correlations up to the pre-installation phase, such as production, deliveries, storage on-site, space constraint, storage duration, buffer stocks, transportation and so forth. FCP production-installation is similar to PC Production-Installation, so the production-delivery-installation process of FCP needs to be defined and time simulation prior to applying FCP on site is needed as well.

The procedure of FCP production is as shown in Figure 1. Firstly, there is a free-form building design, FCP data are extracted, a form is manufactured using a CNC machine, and then FCP is produced and installed [5,6,20]. Among these stages, manufacturing a form using CNC machine, and producing and installing FCP are part of FCP Production-Installation((3)~(5) of Fig. 1). So, a simulation is carried out.

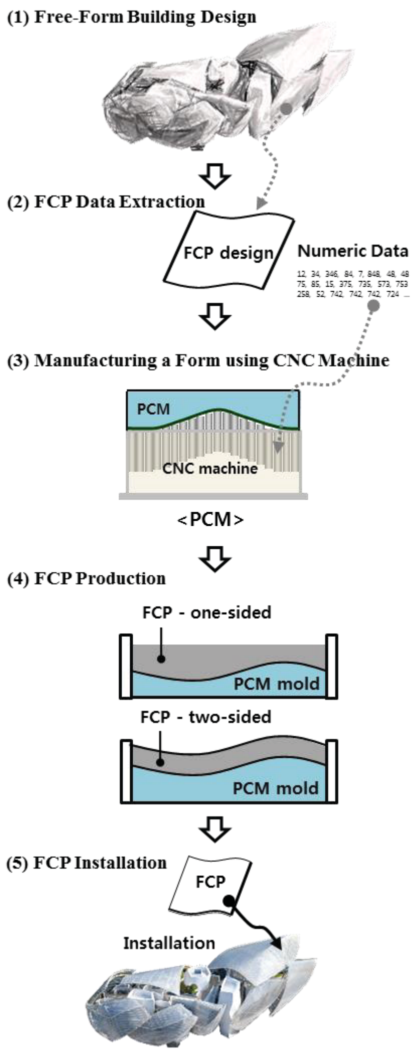

FIGURE I
FCP OF CONPEPT[5]

III. PRODUCTION-INSTALLATION SIMULATION MODEL FCP

Prior to implementing a simulation for estimation of FCP production-installation time, algorithms are built as illustrated in Figure 2. FCP production-installation process is defined and the duration of this process is estimated. By reviewing the process, simulations models of FCP production-installation are proposed if the process satisfies the time of each phase, and the simulation is executed. Using a prospective model chosen from the models, a schedule plan is prepared and the procedure is completed.

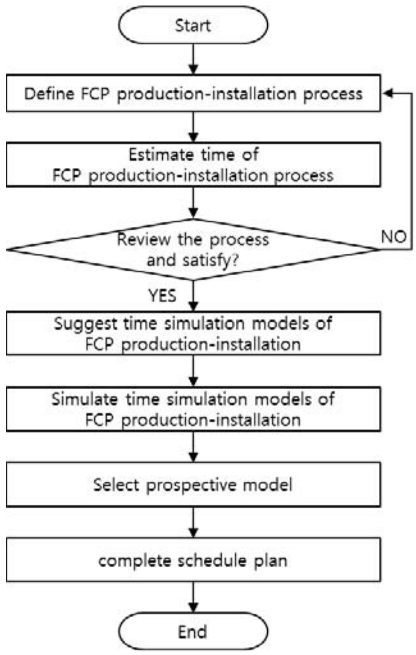

FIGURE II
ALGORITHM FOR FCP PRODUCTION-INSTALLATION

As shown in Table I, construction process is defined and the time required for each phase is analyzed. The phases are divided into Production of FCP, Delivery of FCP and Installation of FCP. 'Production of FCP' involves operation of CNC machine, preparation of PCM, PCM addition, PCM cooling, PCM separation, concrete pouring, curing & form removal and FCP separation. 'Delivery of FCP' is delivering the FCP, and 'Installation of FCP' involves FCP lifting and FCP fixing [22]. Each task is identified by A_{i-1} ~ A_{i-5} signs, and here, i refers to the FCP number, j construction type number, and t_{i-j} the estimated time required per work type. These are given to set a production-installation plan and express it into an equation.

TABLE I
ESTIMATED TIME OF PHASES[5]

Work Type Number (A_{i-j})	Work Type	Estimated Time Required (t_{i-j})	Remark
A_{i-1}	PCM production by CNC Machine	25	· n : sequential mold number · 1day=8hr
A_{i-2}	PCM Finishing	5	
A_{i-3}	Concrete Casting	30	
A_{i-4}	FCP Curing	480	
A_{i-5}	FCP Installing	60	

Time required of formwork fabrication is determined by production equipment planning and method. And FCP installation plan depends on lifting plan and installation technique. It is deemed that formwork finishing, concrete casting, and FCP finishing except for two major tasks in Figure III can be adjusted by mobilizing and controlling resources (manpower). Therefore, production plan and installation plan associated with significant cost limitations and temporal/spatial constraints should be developed preferentially when construction schedule is planned and other tasks need to be controlled with quantity of mobilized resources.

In case of simultaneous concrete casting, the estimation varies as the pouring time and the time required for FCP installation after the first FCP pouring are considered. Figure V is FCP production-installation plan A that the time for FCP installation is longer than the time required for FCP production. Figure IV is FCP production-installation plan B that the time required for FCP production is longer than the time for FCP installation.

Equation 1 is when the time required for FCP production is longer than the time for FCP installation, and equation 2 is when the time for FCP installation is longer than the time required for FCP production.

i) FCP Production-Installation plan A,

$$T_{FCP} = \{(t_{i-1} + t_{i-2}) \times N_{FCP\text{-}casting} + t_{i-3} + t_{i-4}\} + (t_{i-3} + t_{i-4}) \times (N_{FCP\text{-}total}/(N_{FCP\text{-}casting} \times N_{CNC\ machine}) + t_{i-5} \times (N_{FCP\text{-}remainder}/ N_{crew}) \quad (1)$$

ii) FCP Production-Installation plan B,

$$T_{FCP} = \{(t_{i-1} + t_{i-2}) \times N_{FCP\text{-}casting} + t_{i-3} + t_{i-4}\} + t_{i-5} \times \{(N_{FCP\text{-}total}/N_{crew}) \quad (2)$$

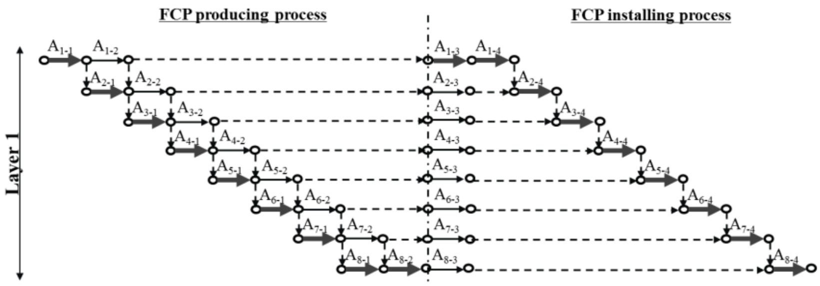

FIGURE III
FCP PRODUCTION-INSTALLATION PLAN UTILIZING ONE UNIT OF CNC MACHINE[5]

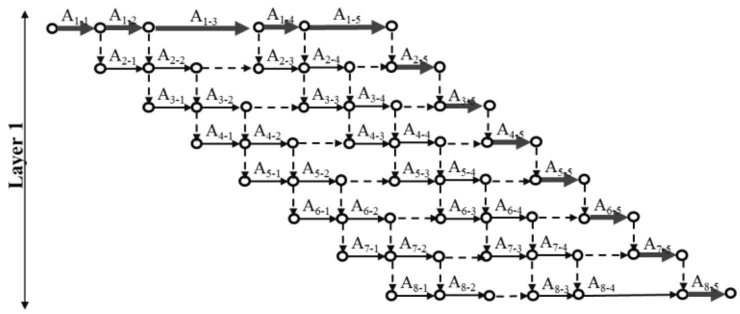

FIGURE IV
FCP PRODUCTION-INSTALLATION PLAN A[5]

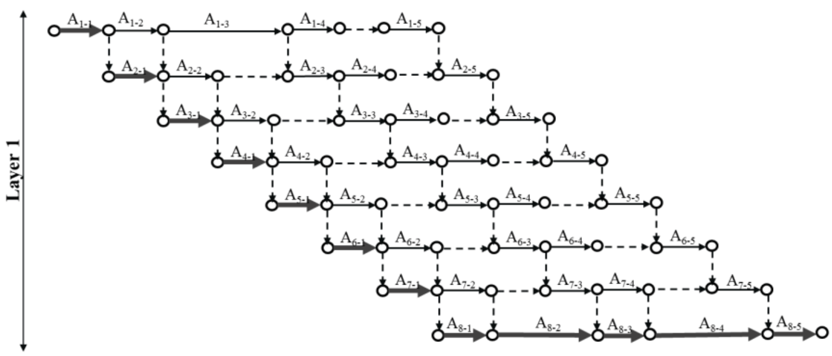

FIGURE V
FCP PRODUCTION-INSTALLATION PLAN B[5]

Here, T_{FCP}: Total time for all FCP Production-Installation
$N_{FCP\text{-}total}$: Total number of FCP
$N_{FCP\text{-}casting}$: Number of FCP upon 1 cycle of simultaneous pouring
$N_{FCP\text{-}remainder}$: FCP number of Remainder after simultaneous pouring
$N_{CNC\ machine}$: Number of CNC machine
N_{crew} : Number of crew(1 crew = 1 crane + labor for FCP installation)

The area of all process is not taken into consideration, and it is assumed that the FCP quality conforms to the requirement. Compared to the free-form roof construction of Qatar National Museum (area: 3,000 m^2), the total area of free-form members to be produced is 3,000m^2 and the average size of FCP is 3×3m. Simulation models of 333 members produced considering economic-feasibility and applying simultaneous pouring are as illustrated in Figure 3. The conditions include use of 4 CNC machines, 4 PCM coolers, simultaneous concrete pouring and 1 crew. 4 members are to be produced through 1 cycle of production-installation and up to 33 members can be loaded in the FCP loading space.

Considering the fact that the number of members upon 1 cycle of production-installation is 4, the time required in case of simultaneous pouring of 32 members is 2815 minutes. Upon production-installation of 333 members, 32 members are poured in 10 times and 13 members a time. When case ii) is applied, 44 days are estimated. Compared to the free-form roof construction of Qatar National Museum (area: 3,000 m^2), the duration for construction reduced 58%.

IV. RESULT

The study established an algorithm for FCP production-installation schedule restricting to PCM, and it made in-situ production possible by choosing a prospective model on the algorithm. The following results were drawn from the study.

1) It was found that process should be defined considering the time required for each phase, including manufacturing of PCM mold, production of FCP (delivery of FCP included) and installation of FCP as the phases are correlated, and then the duration of process should be estimated. In addition, the number of members upon a cycle of simultaneously pouring impacts the time.

2) 58% reduction in time is possible as a result of the estimation made by simulation models proposed through FCP production-installation simulation, against that of the existing free-form building construction.

The algorithm developed can be used to draw an optimal time of FCP Production-Installation, and additional studies on FCP production-installation simulation models should be conducted to identify a concrete layout per process of two-sided PCM. Such should be verified through application to construction sites.

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