5th World Congress on Civil, Structural, and Environmental Engineering (CSEE'20)
~~Lisbon, Portugal~~ Virtual Conference – October 2020
Paper No. ICSECT 133
DOI: 10.11159/icsect20.133

Production Planning of Free-form Concrete Panels using 3D Plastering Technology

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***Abstract* -** A technology has been developed to produce low-cost high-quality FCP (free-form concrete panel) using materials such as glass and pulp. However, FCP production and installation should meet required schedules in order for such technological development to be applied in practice. If it is not possible for the production to satisfy the installation schedules, sufficient lead time should be granted; otherwise, an additional 3D plastering machine is required. This then would give rise to cost and time conflicts. Therefore, an analysis on processes and influential factors relating to FCP production-installation is necessary after which algorithms should be created to link these processes and factors in a systematic method. This study is aimed at production planning of free-form concrete panels using 3D plastering technology. For the purpose of this study, an influential factor analysis and production planning shall be performed in a phased approach. The results of this study are expected to be used as a crucial reference in developing models that can simulate FCP production-installation in various ways.

***Keywords*:** Free-form concrete panel, 3D plastering technique, production plan, lead time.

1. Introduction

A technology has been developed for rapid production of low-cost high-quality FCP (free-form concrete panel) using materials such as glass and pulp [1, 2, 3]. In particular, a FCP production system was built by Son, Kim, and Kim (2019) using RTM (rod type mold) and a 3D plastering machine through years of research [4, 5]. However, FCP production and installation should meet required schedules in order for such technological development to be applied in practice [6, 7, 8]. If it is not possible for the production to satisfy installation schedules, sufficient lead time should be granted; otherwise, additional CNC shaping and 3D plastering machines are required [9, 10]. This then would give rise to cost and time conflicts although time requirement is satisfied. For example, if a construction work is not finished according to the required schedule, liquidated damages should be paid for the delay [11, 12]. If the resulting additional cost exceeds the expense required for adding a machine, a decision for the latter should be made. However, machines cannot be added indefinitely. An accurate analysis on the issues related to cost and time conflicts should be performed to calculate and determine an adequate number of machines. Therefore, an analysis for processes and influential factors relating to FCP production and installation is necessary after which algorithms should be created to link these processes and factors in a systematic method.

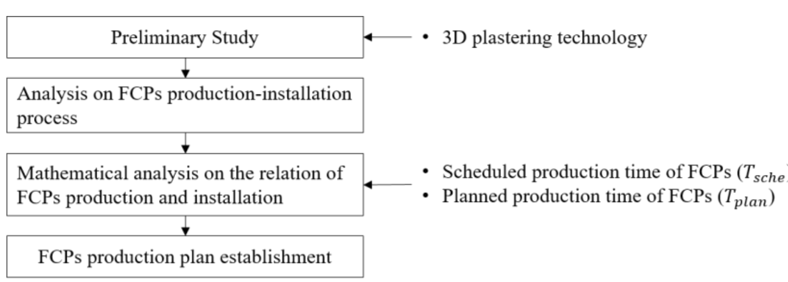

Fig. 1: Methodology.

This study is aimed at production planning of free-form concrete panels using 3D plastering technology. The study process is described in Figure 1 as follows: First, the FCP production-installation process shall be analyzed through which influential factors will be generated; Second, the relation of the generated influential factors shall be analyzed mathematically; Third, an FCP production planning shall be done by reflecting the analysis results. Later, the results of this study are expected to be used as a crucial reference in developing models that can simulate FCP production-installation in various ways.

2. Preliminary Study

2. 1. Overview of FCPs production using 3D plastering technology

This study employs a concept of FCP production as described in Figure 2. First, a free-formed structure is designed by BIM concept as can be seen in Figure 2 (a). FCP production data will be extracted automatically from the BIM design model at this point [3]. The extracted FCP production data will automatically be transferred to a CNC shaping machine as depicted in Figure 2 (b) [4]. The rods on the CNC machine will be operated according to the transferred FCP data by which corresponding RTM rods will be driven to shape the desired free-form structure. [5]. Here, RTM serves the role of a mold that can be used repeatedly with no limit [13]. Next, FRC (fiber reinforced concrete) gets plastered on RTM to produce FCP as depicted in Figure 2 (c) [3].

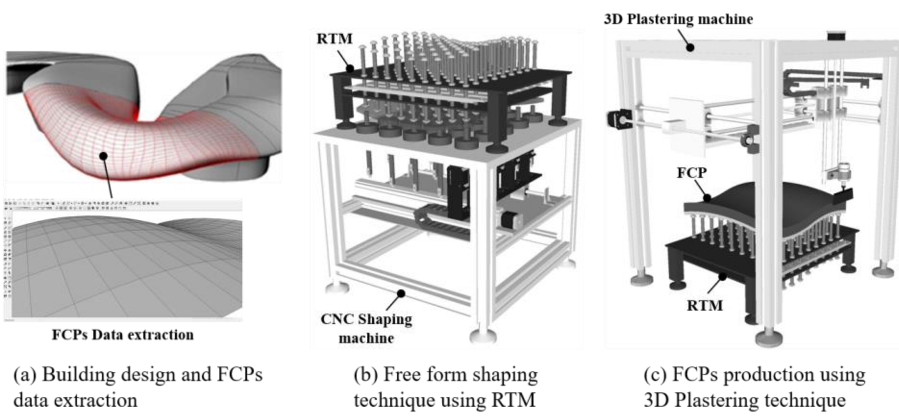

Fig. 2: Overview of FCPs production using 3D plastering technology [3, 4, 5, 13].

Using this study's 3D plastering technique, it is far more economical than the conventional method of processing EPS (Expandable Polystyrene), woods, acryl glass, PCM (Phase Change Material) to build molds and FCP production can be expedited as well [14, 15, 16, 17]. Moreover, FRC made of glass or pulp has a superior quality than other materials such as metal, glass or plastic in terms of construction and maintenance which is also cost effective [18, 19, 20].

2. 2. FCPs production process analysis

The production process for one FCP can be found in Figure 3. FCP production process is composed of 6 phases in total that can largely be categorized as follows: raw material preparation; mold production; FCP production; and, curing [3, 4, 5, 13]. First, glass and pulp fiber - raw materials for FCP - shall be made ready for use (step 1). The first dry mixing is carried out according to the mixing ratio designed for specific product characteristics. The second wet mixing can also be performed as necessary (step 2). Next, RTM is placed on the CNC shaping machine which will shape a free-form structure (step 3). Here, the free-form structure shaped by the CNC shaping machine gets reproduced by RTM's back-up rod [4]. When the free-form structure is shaped on RTM, the back-up rod is fixed and RTM is removed from the CNC Shaping machine. The separated RTM is moved to the 3D plastering machine to go through a process of its upper part being plastered with cement complex such as FRC, troweling, and then cutting and grinding as per required size (step 4) [3]. The plastered RTM after step 4 is moved to the first curing machine for atmospheric steam curing. When the first curing is finished, FCP with RTM is moved to the autoclave machine for the second high-pressure, high-temperature curing (step 5). When FCP gets removed from RTM after the first and second curing processes are complete, it goes through inspection and shipping processes to be supplied at the applicable construction site (step 6). These processes (step1~6) are repeated for FCP production.

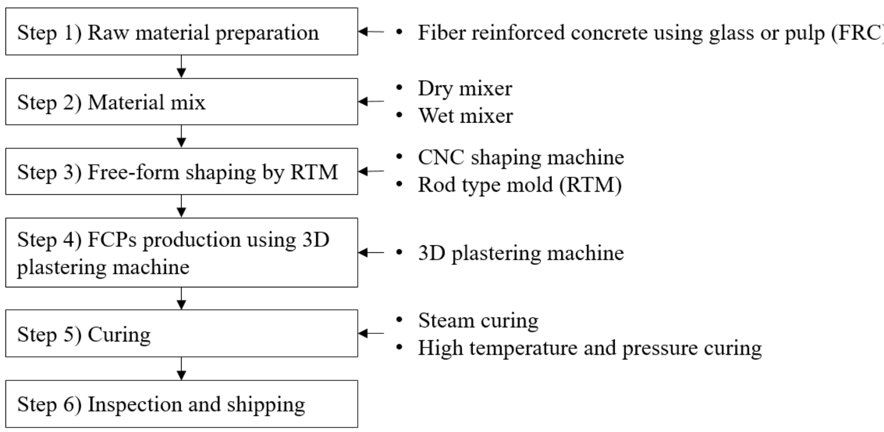

Fig. 3: Production process of an FCP [3, 4, 5, 13].

3. Production planning of FCPs using 3D plastering technology

For practical application of the technology included in this study, machine productivity and the amount of inputs should be adjusted to establish a production plan that corresponds to a given installation schedule. In case FCP production fails to meet the required timeline, sufficient lead time should be ensured or additional machines should be made available. This then would give rise to cost and time conflicts [9, 10]. Therefore, a mathematical analysis on the relation between production and installation will be performed in this study as described in Figure 1, and algorithms will be suggested for a systemized production planning based on the formulae and relevant parameter value (the number of machines) changes resulting from the analysis.

3. 1. Scheduled production time of FCPs

For FCP production, a lead time must be secured before installation as can be seen in Figure 4. All FCP production activities should be finished with a time lag before the final installation is completed [13]. In other words, the production planning should be performed dependent on the installation schedule [9].

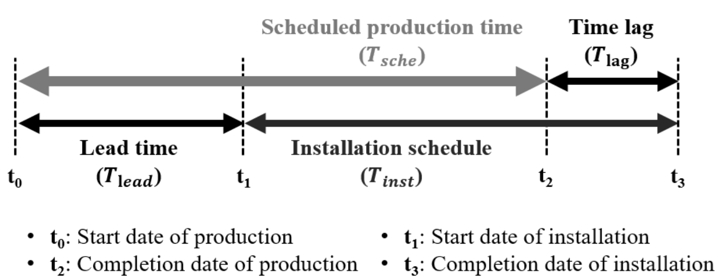

Fig. 4: Relation of FCPs production and installation [9, 13].

$$T_{sche} = T_{inst} + T_{lead} - T_{lag} \quad (1)$$

Here, T_{sche}: scheduled production time, T_{inst}: scheduled installation time, T_{lead}: lead time for FCPs production, T_{lag}: time lag for final installation

The scheduled production time (T_{sche}) is calculated by first adding up FCP's installation time (T_{inst}) and Lead time (T_{lead}), and then subtracting the Time lag (T_{lag}) from the sum as described in Formula (1). Through formula (1), the planned production time (T_{plan}), in which production cycle is reflected, reviews the possibility to produce the entire amount of FCPs within the required schedule (T_{sche}). As such, this study has analyzed the relation between FCP production and installation schedule and expressed it mathematically. In the next section, detailed explanation will be provided for calculating the planned production time (T_{plan}) that reflects the production cycle.

3. 2. Planned production time of FCPs

The most important parameter in producing all FCPs within the required timeline is the number of machines. However, it is desirable to use as few machines as possible to the extent that the required timeline is satisfied because additional cost gets incurred for machine expansion. This then comes down to cost and time conflicts [9]. The essence of this study is to simulate an optimal number of machines to produce all FCPs within the required schedule.

$$T_{plan} = T_{cycle} \times N_{cycle} \quad (2)$$

Here, T_{plan}: planned production time, T_{cycle}: one cycle time of FCP production, N_{cycle}: number of cycle

In this section, algorithms will be created to calculate FCP production time which reflects production cycle and quantity. The planned production time (T_{plan}) which reflects production cycle and quantity is calculated by multiplying one cycle time for FCP production (T_{cycle}) and the number of cycle operation (N_{cycle}) as described in Formula (2). Here, the core parameters that will determine one cycle time (T_{cycle}) are the number of machines made available for FCP production cycle and the time required for each activity. The algorithms suggested in this study should be used to perform a precise analysis on the planned production time (T_{plan}) according to changes in these parameters.

3. 2. 1. One cycle time of FCP production (T_{cycle})

In order to determine one cycle time for FCP production (T_{cycle}), a single FCP production process depicted in Figure 3 is divided into 3 activities as can be seen in Figure 5. Here, it is assumed that all the raw material preparation and mixing are ready at the plant in advance.

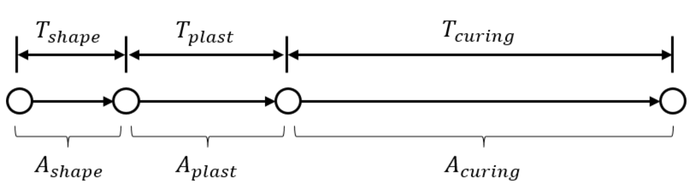

Fig. 5: Production activities of an FCP [9, 13, 21].

Figure 5 describes a single FCP production process comprised of free-form structure shaping (A_{shape}) by the CNC shaping machine, FRC plastering on RTM (A_{plast}) by the 3D plastering machine, and curing (A_{curing}) all of which work together to produce one FCP. This is described in Figure 3 as steps 3 to 5. In addition, time required for each activity is defined as T_{shape}, T_{plast}, and T_{curing}. respectively.

Accordingly, this study defines a FCP production cycle as in Figure 6. Here, one unit of CNC shaping machine can cover one production cycle, and the machine consecutively shapes free-form structures on RTM. Here, the time taken to to shape a free-form structure on RTM (T_{shape}) is shorter than time taken to plaster FRC using the 3D plastering machine (T_{plast}). This is expressed as $T_{shape} < T_{plast}$. In order to achieve efficient operation overall with no time delay for FCP production, production, a number of 3D plastering machines are required for one CNC shaping machine. As a result, it is assumed in this in this study that one production cycle is composed of one unit of CNC shaping machine and (T_{plast}/T_{shape}) units of 3D plastering machine.

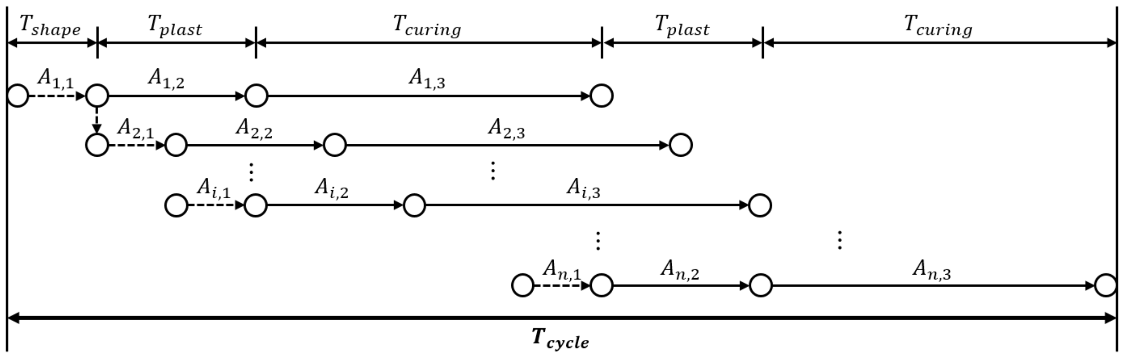

Fig. 6: A production cycle of FCPs [9, 13].

The production cycle for one FCP in Figure 6 can be explained in detail as follows: One unit of CNC shaping machine gets started for the first FCP production activity and shapes one free-form structure on RTM ($A_{1,1}$), after which it is moved to the next structure shaping activity. This point is the beginning of producing the first FCP ($A_{1,2}$). In other words, at the point where the first FCP production is complete ($A_{1,3}$), structure shaping on the nth RTM gets finished. Next, the CNC shaping machine is moved to the 1st production activity. As explained in Formula (3), time required for this process is defined as one cycle time for FCP production (T_{cycle}), and it is the sum of time for shaping a free-form structure on one RTM (T_{shape}) and time for producing 2 FCPs ($T_{plast}+T_{curing}$).

$$T_{cycle} = T_{shape} + 2 \times (T_{plast} + T_{curing}) \tag{3}$$

Here, T_{shape}: free-form shaping time by RTM, T_{plast}: FCP production time using 3D plastering machine, T_{curing}: curing time

3.2.2. Number of cycles (N_{cycle})

The number of FCP cycle operation (N_{cycle}) is the number of FCP production cycles required to meet the entire production quantity as explained in Figure 6 [9]. This is calculated by dividing the entire quantity (Q_{cycle}) by the quantity per production cycle (Q_{cycle}) as in Formula (4). Here, the quantity per production cycle (Q_{cycle}) is calculated by multiplying the number of lines per production cycle (N_{line}) and the number of CNC shaping machines (N_{cnc}).

$$N_{cycle} = \frac{Q_{total}}{N_{cnc} \times N_{line}} \tag{4}$$

Here, Q_{total}: the entire quantity, N_{cnc}: number of CNC shaping machines, N_{line}: number of lines per production cycle

In Formula (4), the number of lines per production cycle (N_{line}) is the same value of n in Figure 6. For the production cycle in Figure 6, the time taken to shape a free-form structure on (n-1) unit(s) of RTM (T_{shape}) is identical to the time producing one FCP (T_{plast}+T_{curing}) and can be expressed as Formula (5).

$$N_{line} = \frac{T_{plast} + T_{curing}}{T_{shape}} + 1 \tag{5}$$

As such, the production time which reflects the production cycle and quantity can automatically be calculated by using formulae suggested in this study. Also, various production plans can be established through changing values of diverse parameters defined in each formula.

3. 2. 3. Review of production time

Using the mathematical algorithms suggested so far, calculated values for the scheduled production time (T_{sche}) and the planned production time (T_{plan}) should be compared against each other to check whether all FCPs can be produced within the time for installation. This means that $T_{plan} \leq T_{sche}$ should be satisfied. In case of $T_{plan} \geq T_{sche}$, the lead time should be extended or CNC shaping and 3D plastering machines should be added to complete production within the required schedule. The model in this study supports calculating the production time reflecting the installation schedule through changes in various parameters such as lead time and the number of machines. This will allow various alternatives for FCP production planning.

4. Planning process for the FCPs production

FCP production planning by using the technology included in this study can proceed as in Figure 7. First, the scheduled production time (T_{sche}) should be calculated reflecting a given installation schedule. Here, the lead time can be configured as a parameter to simulate the scheduled production time according to the changing lead time. Second, the planned production time (T_{plan}) should be calculated based on FCP production cycle and quantity. Here, the core parameter for calculating the FCP production cycle is the number of machines from which production time can be simulated according to the changing number of machines.

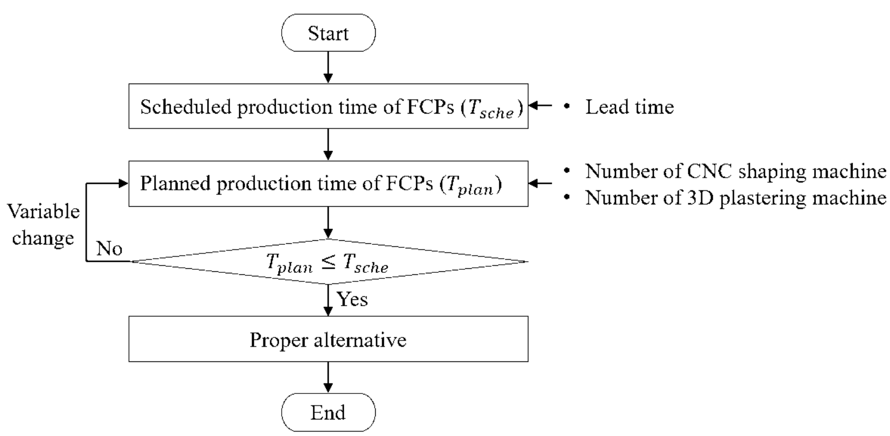

Fig. 7: Planning process for the FCPs production.

Third, a comparative review should be performed on the calculations for the scheduled production time and the planned production time. It should be assessed through this review whether all FCPs can be produced within the required schedule. If it is difficult for the production to meet the installation schedule, the number of machines should be adjusted to meet the required schedule. As such, the algorithms included in this study can be helpful for a systematic FCP production planning reflecting the installation schedule. The FCP production algorithm depicted in Figure 7 is supportive of production and installation of all FCPs according to the required schedule; thus, can be used as an important reference for developing various FCP production-installation simulation models.

5. Conclusion

In this study, the relation between FCP production and installation was analyzed and mathematical algorithms were suggested linking the two. The results of this study are as follows: First, the suggested algorithms analyzed the relation between FCP's complicated production and installation in a mathematical manner; Second, a suggestion was made for FCP production planning in consideration of the installation schedule. This supports FCP production-installation to be completed within the required schedule; Third, the suggested algorithms can be used to simulate various calculations for different construction site conditions by changing parameters such as the number of machines and lead time. Primary parameters can always be changed and applied to the mathematically linked algorithms. If there are unavoidable constraints in the parameters such as the number of machines, lead time, and the number of RTM, such parameter can be determined as a primary parameter for simulation and the remaining parameters can be dependent. In order to perform this process easily and quickly, the suggested algorithms should be developed into a computerized software. The results of this study are expected to be used as a crucial reference in developing models that can simulate FCP production and installation in various ways.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MOE) (No. 2017R1D1A1B04033761).

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MOE) (No. NRF-2018M2B2B1065635).

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