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# Automatic Panelizing Algorithms of Free-form Buildings

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***Abstract: New technologies using a CNC machine are being developed to reduce the production cost of free-form buildings. For production of free-form members using such technologies, vast free-form buildings should be first split into multiple panels that are productible. Taking into consideration of the curved surface of free-form members, the segmented free-form panels may vary in shape and size, which may cause a lot of errors. In addition, it is time-consuming for the work. However, the current panelizing work is completed with the trials and errors of engineers and architectural designers even in large-scale projects, which results in increased construction duration and cost. Thus, it is necessary to develop a technology for panelizing free-form panels so as to maximize the economic feasibility of production technologies for free-form concrete members. The study intends to develeop automatic panelizing algorithms of free-form buildings considering the curved surface and size of free-form panels and the production conditions. The developed algorithms will be useful in applying the production technologies of free-form buildings using CNC machine and reducing the cost.***

***Keywords: Free-form panel, Automatic, Panelizing, Algorithm, Building, CNC machine***

## I. INTRODUCTION

New technologies using a CNC machine are being developed to reduce the production cost of free-form buildings. For production of free-form members using such technologies, vast free-form buildings should be first split into multiple panels that can be produced. Taking into consideration of the curved surface of free-form members, the segmented free-form panels may vary in shape and size, which may cause a lot of errors. In addition, it is time-consuming for the work is difficult. However, the current panelizing work is completed with the trials and errors of engineers and architectural designers even in large-scale projects, which results in increased construction duration and cost. Thus, it is necessary to develop a technology for panelizing free-form panels so as to maximize the economic feasibility of production technologies for free-form concrete members. The study intends to develop automatic panelizing algorithms of free-form buildings considering the curved space and size of free-form panels and the production conditions.

## II. PRELIMINARY STUDY

Studies related to free-form buildings are largely conducted in two different perspectives - design and construction, and the former are on proposing the building's design process, characteristic analyses of shapes and analyses of the design technology concept and the latter are on pointing out the problems of free-form buildings. In addition, there are studies analyzing the cases of BIM-based free-form concrete design and construction, yet there is no practical study on panelizing.

As examining the relevant studies in detail, Bae et al. [3] proposed digital design directions through analyses of background and cases applied with digital design process in constructing free-form buildings. Lyu [1] analyzed the background and cases applied with digital design process in constructing free-form buildings with five different standards - Sectioning, Tessellating, Folding, Contouring and Forming. Park et al. [4] introduced a case of free-form building using T-shaped, light steel manufactured using a CNC machine, Ryu and Kim [5] analyzed the design and construction of Tri-Bowl type free-form concrete members based on BIM and Ryu [6] proposed the optimization of digital design taking into consideration of constructability of free-form structures. Meanwhile, Lee [2] indicated the problems of free-form buildings with a lawsuit case on Stata Center of MIT completed in 2004, in terms of automatic creation of designs, panelizing, manufacturing, measurement, cooperation and legal

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issues. As described above, the studies related to free-form buildings are in the early stage, limited to case studies, analyses of problems and proposal of design process. Along with the development of computer processing abilities, 3D design technologies like BIM and CNC processing of design information have reached a significant level. Furthermore, free-form buildings are frequently constructed based on a huge sum of capital in advanced countries, yet there are not enough practical studies on panelizing of FCP for free-form buildings from a construction aspect [7, 8, 9]. Choi et al.[10] proposed freeform optimization process to mitigate the risk from happening at construction stage. Using BIM, visualization, parametric model and automation functions, various design alternatives are made to apply curvature analysis, panelization, panelization evaluation, and panel optimization for most efficient solution.

## III. Development of FCP Segmentation Algorithms

The purpose of this study is to develop a technology to panelize FCP considering the construction of free-form buildings, to extract individual FCP information (location, size, shape, volume, weight and etc) and to transfer the information to a program that operates CNC machines. Figure 3 is the segmentation of free-form members for 'D' Plaza. The size of panels for the building envelope was adjusted depending on the direction of curved surface, curvature and function. In addition, the direction of panelizing was set considering aesthetic factors and constructability. According to the engineers and architectural designers who participated in the 'D' Plaza project, the size and shape of panels were segmented based on their experiences and decisions as well as the trials and errors, which were time-consuming. Automatic panelizing algorithms of free-form buildings proposed in the study are to optimize panelizing in order to reduce the hours and manpower and to prevent errors from occurring.

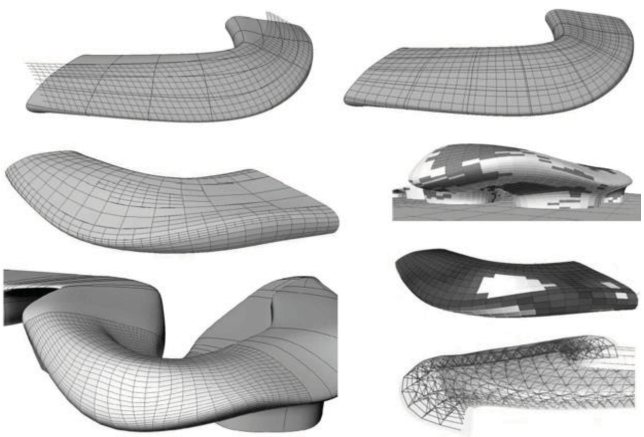


Figure I
Panelizing for Production and Installation of Free-Form Building Panels

Several critical conditions should be met in panelizing the BIM design for FCP production. As shown in Figure 2, FCP should be panelized into sizes that can be produced. The member size and its curvature are limited as produced with CNC machines. Here, the curvature of members depends on the design and characteristics of production equipment. In addition, the size and weight for installation should be taken into consideration. According to the project conditions, FCP size should be decided considering the capacity of lifting equipment (crane), and then BIM design should be panelized. The size and shape that can be installed are decided taking into account of the location of FCP installed in a building depending on the structural characteristics of such building. Aesthetic factor depending on the location of joint should be considered as well in FCP panelizing.

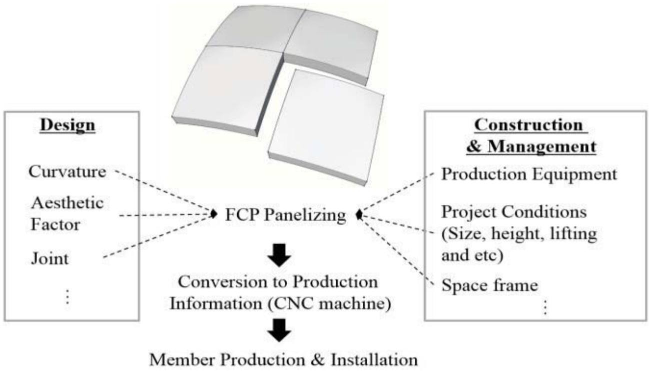



Figure II
Influence Factors for FCP Panelizing

Panelizing is conducted through the process of checking the production and installation conditions, and creating panels using algorithms. Such fundamental limitation is created from the data at production and installation phases, as shown in Figure 3. For FCP panelizing, not only the production, lifting and installation plans should be reviewed, but also the aesthetic aspects for a beautifully-shaped building should be taken into consideration. 'Project DB' on the right of Figure 3 includes all information needed to review a panelizing plan, including the building design, structure and temporary works for construction. After reviewing the panelizing plan per phase, it should be revised if not appropriate, and another panelizing plan should be established. In addition, a technology to convert the established panelizing plan into information that can be produced with CNC machines should be developed along with the panelizing technology. Currently, BIM information of free-form buildings cannot provide data needed for FCP production as well as NC data after panelizing the unit member. Construction engineers should create NC data that CNC machines can recognize based on BIM or CAD information for FCP production. The individual FCP information segmented, in other words FPDB (Free-form Panel DataBase), should be composed of necessary information, including the panel location, size, shape and schedule. FPDB provides engineers with necessary information for FCP production and installation [11].

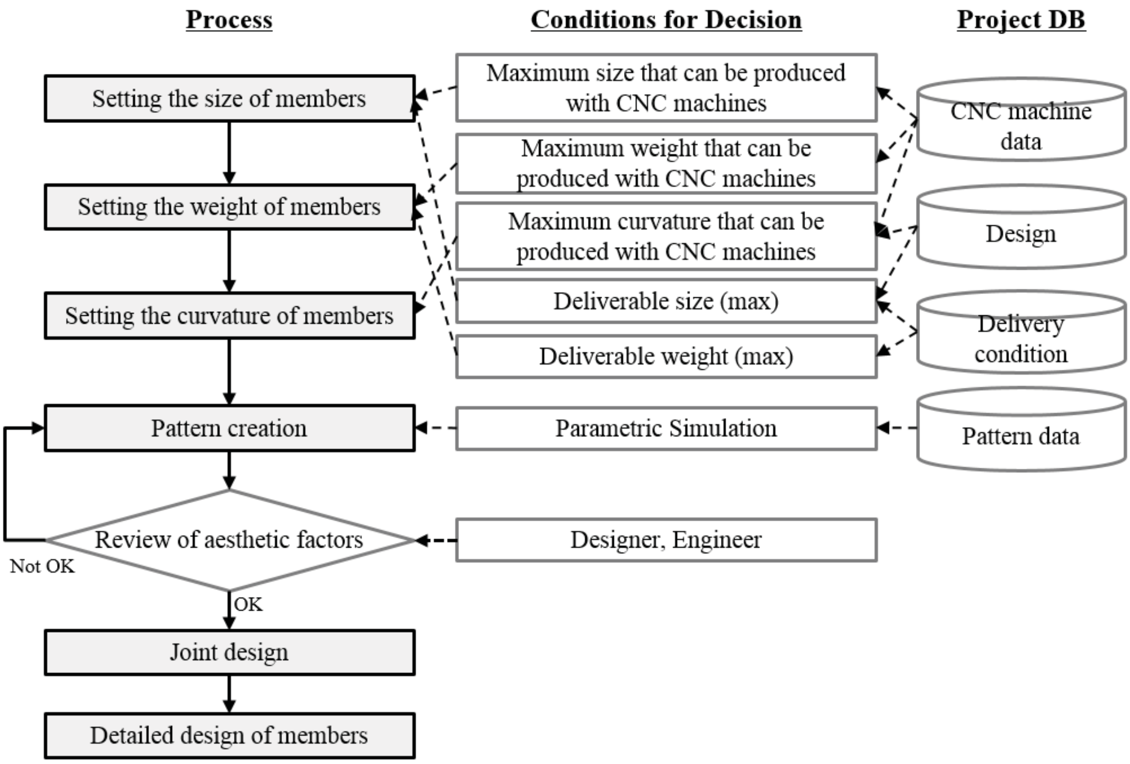



FIGURE III

FCP PANELIZING ALGORITHMS

Constraints of the algorithms are classified into 3 types – size, weight and curvature. For ths size and weight of FCP, the maximum values of both types that can be produced with CNC machines should be considered, and for the curvature of FCP, only the maximum curvature that can be produced with CNC machines is required. Constraints and variables are as defined in Table 1.

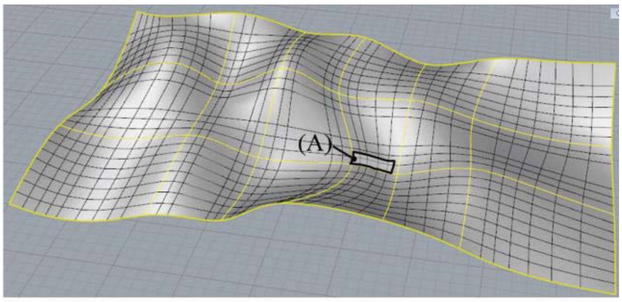
## IV. RESULT

FCP panelizing algorithms use parametric simulation for creation of patterns. The simulation is implemented using the information on size and shape received from data of various patterns. Here, a wide range of pattern plans are drawn by controlling the size according to the curvature within the range permitted by constraints. Figure 4 is an automation of the simulation using Rhino (ver. 5), and 2 different patterns are drawn according to the maximum size setting of unit member after the free-form surface (12m x 6m) is designed. Pattern 1 shown in Figure 4(a) is restricted to 1.2 m × 1.2 m and Figure 4(b) to 0.8 m × 0.8 m to run the simulation. Owing to the constraint of curvature, size per part differs. In particular, (A) and (B) parts with the largest curvature were panelized into small sizes. The detailed algorithms and results will be published through a paper.

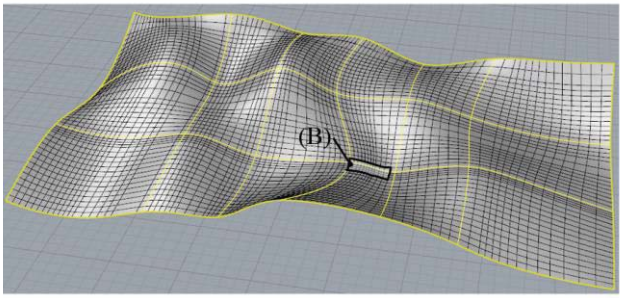
TABLE I

CONSTRAINTS OF PANELIZING ALGORITHMS

| Type | | Constraints | Definition of Variables | |
|---|---|---|---|---|
| Size Limit | CNC Machine | $V_{FCP} \le V_p$ | $V_{FCP}$ : Size of FCP<br>$V_p$ : Maximum size that can be produced<br>$V_t$ : Maximum szie that can be delivered<br>$W_{FCP}$ : Weight of FCP | $W_p$ : Maximum weight that can be produced<br>$W_t$ : Maximum weight that can be delivered<br>$C_{FCP}$ : Curvature of FCP<br>$C_p$ : Maximum curvature that can be produced |
| | Delivery | $V_{FCP} \le V_t$ | | |
| Weight Limit | CNC Machine | $W_{FCP} \le W_p$ | | |
| | Delivery | $W_{FCP} \le W_t$ | | |
| Curvature Limit | CNC Machine | $C_{FCP} \le C_p$ | | |




(a) Pattern 1: Maximum size 1.2m x 1.2m, curvature 0.1 or below

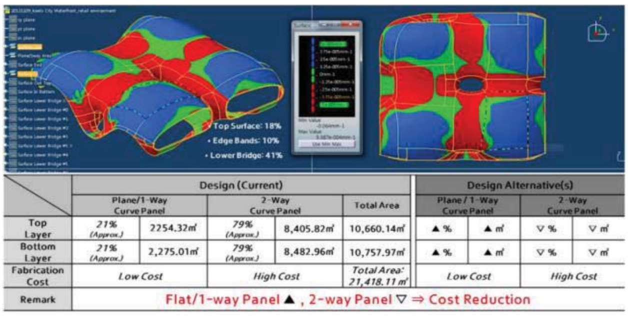



(b) Pattern 2: Maximum size 0.8m x 0.8m, curvature 0.05 or below

FIGURE IV

PANELIZING OF FREE-FORM DESIGNS (RHINO VER. 5)

As it presented in a previous study the panels can be classified according to the curvature, the flat panel refers to a panel without the occurrence direction of curve, the one way panel refers to panels with one direction of curve, and two or multi way panel refers to a panel with two or more direction of curve [10]. Result of implementing design analysis step to the project was seventy-nine percent of total surface area was two way panel and rest, 21% was flat or one way panels. In further study, limited the area to top surface of retail roof which is forty-five percent of total surface area [10].




| | Design (Current) | | | | | Design Alternative(s) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Plane/1-Way Curve Panel | | 2-Way Curve Panel | | Total Area | Plane / 1-Way Curve Panel | | 2-Way Curve Panel | |
| Top Layer | 21% (Approx.) | 2254.32㎡ | 79% (Approx.) | 8,405.82㎡ | 10,660.14㎡ | ▲ % | ▲ ㎡ | ▽ % | ▽ ㎡ |
| Bottom Layer | 21% (Approx.) | 2,275.01㎡ | 79% (Approx.) | 8,482.96㎡ | 10,757.97㎡ | ▲ % | ▲ ㎡ | ▽ % | ▽ ㎡ |
| Fabrication Cost | Low Cost | | High Cost | | Total Area: 21,418.11 ㎡ | Low Cost | | High Cost | |
| Remark | Flat/1-way Panel ▲ , 2-way Panel ▽ ⇒ Cost Reduction | | | | | | | | |

FIGURE V

CLASSIFICATION OF PANEL ON PROJECT [10]

## V. CONCLUSION

The study developed automatic algorithms of free-form buildings taking into consideration of the curved surface and size of free-form panels and production conditions. FCP panelizing algorithms of free-form buildings have the following characteristics.

1) For FCP panelizing, not only the production, lifting and installation plans should be reviewed, but also the aesthetic aspects for a beautifully-shaped building should be taken into consideration.
2) A wide range of pattern plans are drawn by controlling the size according to the curvature within the range permitted by constraints.
3) Panelizing plan should be designed to satisfy 3 constraints – the size, weight and curvature of FCP.
4) Automatic panelizing algorithms of free-form buildings are to optimize panelizing in order to reduce the hours and manpower and to prevent errors from occurring.

It is expected that the algorithms developed will reduce the time and manpower input for free-form building projects since the problems that may occur during the production and installation of free-form members can be prevented by reviewing the constraints upon FCP production and installation as well as aesthetic factors.

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