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Development of Buried Side Molds for Precise FCP Side Geometry

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***Abstract-** With the recently increased demand for free-form architecture domestically and internationally, there has been growing research on mold technology and construction methods to achieve it. But the level of relevant research is still very insufficient. In order to configure free-form curves in buildings, it must undergo a process of producing multiple free-form panels for assembly. There are many limitations in this process using domestic technologies, and the quality of produced free-form panels is also low. In particular, during the course of placing and curing concrete in free-form, there can be shape errors on the side of the mold due to the side pressure of concrete. Therefore, in this study, a buried side molds was developed into make improvements to the errors in shape that occur on the sides of free-form panels. Buried side molds are designed into two different types depending on the shape information for producing panels from BIM. The free-form panel is produced using the two types of forms produced, and they are scanned to calculate each error value. Based on the computed data, it is checked whether the buried side molds fit the research objective. This study requires supplementation through follow-up research, and it is expected that it will be actively used for developing free-form concrete panel (FCP) production technologies in Korea.*

***Keywords:** Free-form Concrete Panel, Side Shape Implementation, Buried side molds*

1. INTRODUCTION

1.1. Purpose of the Research

With the development of science technology both domestically and internationally over the past 20 years, there has been growing demand for various free-form architecture (Jiang, 2021). Accordingly, there has been new design methods and development of construction technologies to reduce the construction period and costs (Kim, 2014). But even as of current, construction of free-form architecture requires significantly more time and expenses compared to fixed-form architecture. Table 1 summarizes issues that occur during the construction of free-form architecture. Construction of the Walt Disney Concert Hall in LA, USA increased from the initial five-year construction period to 16 years due to delays caused by the LA riots and earthquakes, and the construction cost that was initially estimated at 100 million USD increased by 2.5 times (Lee, 2014). Also, the MIT Stata Center had various construction defects such as cracks in the wall due to waterwork issues, which resulted in lawsuits. In the case of Exhibit Hall 2 of KINTEX that was completed in 2011, it was pointed out that construction costs were wasted due to excessive changes in designs that totaled to 68 cases (An, 2011). Currently, technological development that can resolve limitations in costs, time, quality, safety, etc. must be developed to ensure economic feasibility and workability of free-form buildings and to reduce such construction defects.

Table 1: Problems during the construction of free-form buildings

Division	Year	Detail
Walt Disney Concert Hall	2003	Construction period increased by 11 years
MIT Stata Center	2004	Construction cost increased by 2.5 times
KINTEX Exhibition Hall 2	2011	Used 1.5 billion KRW for reconstruction due to cracks and leaks
DDP	2014	Uncertain construction cost predictions and rise of construction costs due to excessive changes in designs

In order to conduct precision construction on free-form buildings, the exterior of the massive structure must be divided into multiple panels at sizes that can be constructed (Lee, 2015). However, due to the nature of free-form curves with various shapes and sizes, partitioned panels have many errors (Son, 2016). In particular, during the process of assembling the separately produced panels, slight errors on the sides of each panel can have a big impact on the construction precision of completed buildings. But there is still very little research on panel sides.

Therefore, this study examines preceding studies on precise side shape configuration and deduces limitations. The biggest limitation of existing side molds was the deformation caused by errors in the sides caused by the structure and due to the side pressure of concrete. This study aims at coming up with a design that improves this to develop a new buried side molds. It is expected that this mold will be utilized for research on domestic FCP panel production technologies.

1.2. Methods and Procedures of the Study

In this study, steel was selected as the material for side molds for configuring precise side form. Steel can be processed easily and can secure sufficient strength that resists the side pressure of concrete, and therefore, it is appropriate to use as materials for FCP. But it also has the weakness that it is a heavy material. Therefore, a molds is used additionally using a wire mesh. Wire meshes are lighter than steel and its cross section that touches concrete increases, therefore making it possible to secure higher adhesion strength.

In addition, side molds produced while producing panels apply the method of burying in the panel. This omits the molds disassembly process to reduce the construction cost, while also increasing workability. This research is carried out in the order as shown in Figure 1 below. First, preceding studies related to side molds per material are examined and the limitations are identified. Afterwards, the CAD program is used to draw up design plans of the buried side molds. The produced side mold is placed on a free-form silicon plate set by the lower CNC equipment to perform panel production experiments. Therefore, the produced free-form panel is scanned, and then margin of error is analyzed using the quality inspection program to verify the precision of the panel shape.

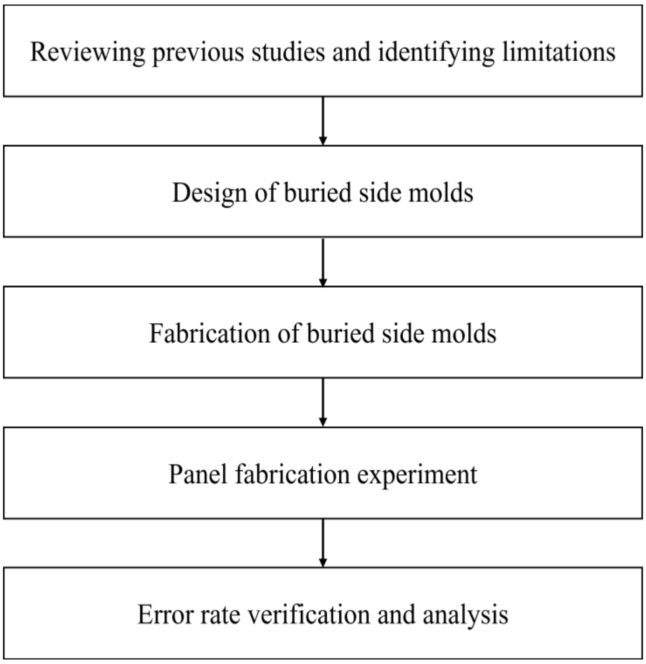


Fig. 1: Procedure for Conduction of Research

2. LITERATURE REVIEW

2.1. Review of Previous Studies

Compared to overseas, Korea has insufficient research on developing commercialization technologies of FCP to configure free-form architecture. And when examining relevant domestic studies, (Park 2012) introduced a case of configuring free-form concrete panels using a CNC processed T-type lightweight steel frame. Also, (Ryu 2012) analyzed FCS design and construction cases with Tri-Bowl forms based on BIM, and this was performed at case-study levels. In foreign studies, (P. Mandl et al., 2008) used CNC processing to produce EPS-molds and (ToyoIto & Associates 2006) used a wood mold processed using CNC equipment to configure free-form concrete supplementary materials. With such CNC processed molds, it is possible to configure concrete shapes, but it is impossible to reuse the molds, thus lowering economic feasibility, and therefore requires development of free-forms that make improvements to this. Table 2 summarizes preceding studies on domestic and foreign free-form building construction technologies with a table.

Table 2: A preliminary study on the construction technology of free-form buildings in Korea and abroad

Thesis title	(Author year)	Content
Development of the Free-formed Concrete Structure Construction Technologies using 3D Digital Design	(Youngmi Park et al., 2012)	Proposal of configuration method for T-type lightweight steel frame using CNC equipment.
Case Study of Concrete Surface Design and Construction Method for Freeform Building Based on BIM -Focused on Tri-Bowl, Korea-	(Hanguk Ryu & Sungjin Kim)	Proposed design and construction method for concrete surface frame of free-form buildings based on BIM.
Free-forms in composite constructions, the new house of music and music theatre 'MUMUTH' in Graz	(P.Mandl et al., 2008)	Produced EPS-formwork using CNC equipment.
Meiso no Mori Crematorium Gifu	(ToyoIto & Associates 2006)	Produced concrete supplementary materials using CNC equipment and wooden molds.

2.2. Limitations of Existing Technology

Table 3 shows case studies that produces side molds using various materials PCM is a material that can change states between liquids and solids according to temperature changes, and they include wax, silicon, etc. Molds used for FCP production in the past were produced for one-time use, and they have the problem that they cannot be used again. Accordingly, (Lee 2015) produced a free-form using wax to produce FCP and after producing the FCP, the PCM molds was heated and melted to separate the compounds and PCM, and this process was repeated to produce another molds. But this had the limitation in that productivity and efficiency was reduced. To solve this issue, (Yun 2022) produced a free-form using silicone. Due to the material nature of silicone, it adheres according to the free-form curves and can vary, giving it excellent efficiency. However, silicone side molds have the limitation in that when producing FCP, it can be pushed due to the side pressure of concrete, thus causing errors. And therefore, this study aims at developing materials and structures with sufficient strength that can resist the side pressure of concrete.

Existing molds for FCP production can configure the lower curves with CNC (Computer Numerical Control), but it has the problem that precision configuration is not possible on the side shape due to pushing of the silicone. (Jeong 2020) developed a variable side mold that can freely configure shapes using steel as the material. This is produced as steel and can resist side pressure of concrete, and it is easy to adjust curves and lengths, and can be reused. But variable side molds have the limitation in that it is produced by combining with multiple plates, and the structural grooves can cause a large error on the side of the FCP. Therefore, this study came up with design plans for improving the precision on the side shape.

Table 3: A precedent study of side formwork

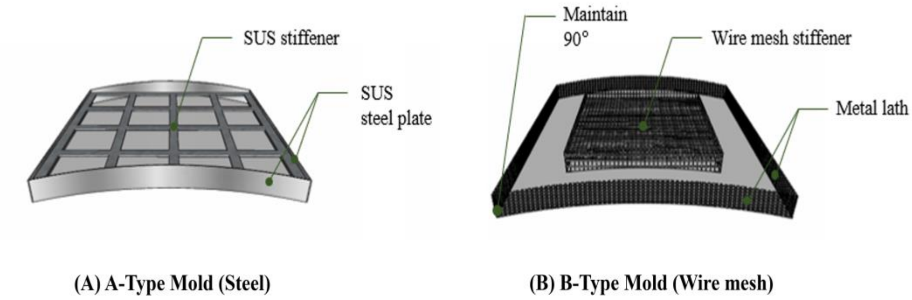
Thesis title	(Author year)	Content
Development of PCM-enabled Atypical Concrete Segment Production Process	(Donghoon Lee & Sunkuk Kim 2015)	Developed variable molds technology with PCM, an economic material that can be recycled.
Development of Two-Sided CNC and Side Mould Control Equipment for Automatic Manufacture of Free-form Concrete Panel	(Kyeongtae Jeong & Donghoon Lee 2021)	Developed 'variable side mold' using equipment for automatic FCP production.
Development of Connection Technology and Operational Technology for the Lower Mold of Free-form Concrete Panels	(Jiyeong Yun & Donghoon Lee 2022)	Used PCM side molds in the process of producing free-form concrete panels.

3. DEVELOPED BURIED SIDE MOLDS

3.1. Buried Side Molds Design

Buried side molds was designed as A-Type using steel plates and B-Type using wire meshes.

Figure 2 is a schematic diagram that drew A-Type and B-Type in 3D. The outer part of A-Type has four sides made of SUS steel. It is composed of two sides with curves and two sides that are straight. At the corner joint part, the angle of the curved side and the straight side was designed at 90°. For the interior of the molds, reinforcement was inserted in the material to raise the strength of the molds. This can also prevent deviation of internal and external forms caused by the side pressure of concrete. The exterior of the B-Type has four sides made of metal lath. Like the A-Type, it has two curved sides and two straight sides. But the thickness of 0.6mm and there are differences in terms of thickness with the SUS steel plates. Therefore, the weight of the produced panel can be lowered. Also, by inserting reinforcement using a wire mesh inside, the strength of the molds was increased, and it prevents detachment of buried side molds and concrete during panel production. This can simultaneously prevent cracks in concretes around the panel.



(A) A-Type Mold (Steel)

(B) B-Type Mold (Wire mesh)

Fig. 2: Buried Side Molds Conceptual Diagram

3.2. Fabrication of Buried Side Molds

Materials are purchased according to the devised design. The materials are shelf products. Thick SUS steel plates are cut using laser and relatively thin metal lath and wire meshes are produced as guide models using a 3D printer, and then cut with a grinder. SUS steel plates of A-Type are welded with each of the subsidiary material, and the metal lath of B-Type is bonded using epoxy. Detailed photos of each of the produced forms are as shown in Figure 3.

(A) A-Type

(B) B-Type

Fig. 3: Molds Detailed Picture

4. PANEL FABRICATION EXPERIMENT USING CNC EQUIPMENT AND BURIED SIDE MOLDS

4.1. Experimental Overview and Purpose

This experiment checks whether the buried side molds developed in this study configure precise side shapes of the panel. Therefore, experiments are carried out focusing on the side of the free-form panel. Panels are produced separately for A-Type and B-Type for comparison. They both bury the forms in the concrete, and therefore does not have a form disassembly process. After hardening, the perfection of the mold is judged using the error values on the sides of the completed panels.

4.2. Experimental Process

The panels to be produces are raised 18mm from the plane. The curves generated at this time are manually configured in the CNC equipment. First, CNC equipment viewed horizontally and the panel to be produced using CAD are drawn to calculate the values. The load movement value considering each joint value based on the six bolts arranged every 100mm is calculated. The calculated value is as shown in Figure 4.

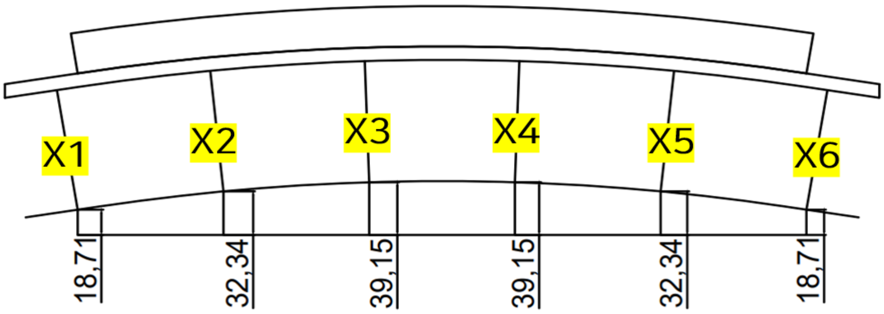


Fig. 4: Rods Rotation Calculation

The silicone plate is placed on top of the CNC equipment for which the curve was set, and the buried side molds is placed at its proper side. The PVA fiber concrete mixed earlier is placed in the form. Laying is omitted in order to prevent the shape from falling apart. Use a paddle to plaster so that it can be placed evenly in the corners and internal form. After 24 hours, the concrete panel hardened together with the form is removed from the silicone plate for resting. The free-form panel production process is the same for A-Type and B-Type, and they are as shown in Figure 5.

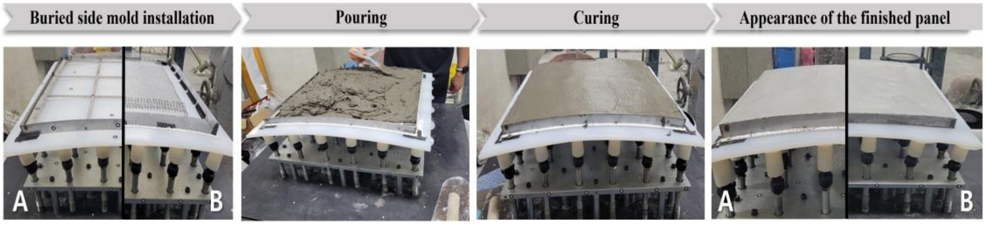


Fig. 5: Panel Fabrication Process

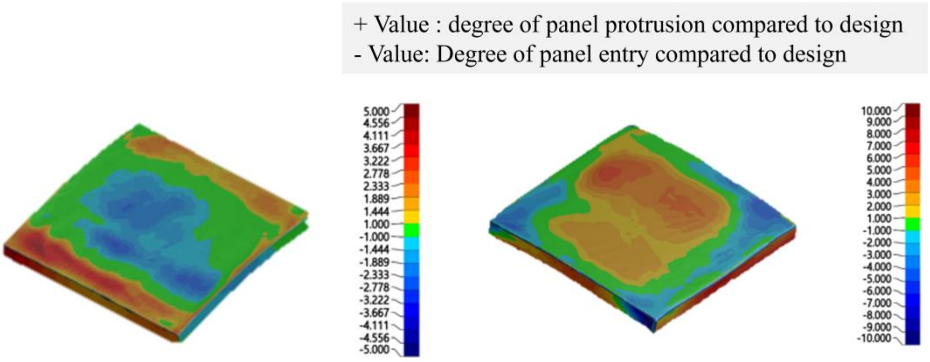
4.3. Experimental Verification

The error value is analyzed using the program called VXelements. In order to analyze the error values, the shape of the free-form panel designed with CAD and the scanned shape of the actually produced panel are compared and checked. The experiment verification method is as shown below. First, the zero point of the scanner was adjusted and then the target sticker is attached to the produced free-form panel. Afterwards, the panel is slowly scanned up/down/left/right. When the light from the scanner is reflected off the attached sticker and the shape is captured, it is checked through monitoring. For the completed scan data, the background is removed except for the panel to be analyzed. Also, cracks and bubble holes that can affect error undergoes flattening for compensation. Once all procedures are completed, the range of error of the panel is set. This study was experimented mainly on the side, so only the panel side error value is analyzed. Therefore, the values that arranged the recorded values were summed up in an Excel sheet, and it is as shown in Table 4.

Table 4: Side error measurement results

Type	Size	Minimum	Maximum	±	SD
A	-2.332	4.753	7.058	1.469	-2.332
B	-12.531	8.846	21.377	3.145	-12.531

The maximum value is used for analyzing the error value. This refers to the maximum vertical error value generated from the design side of the standard design shape. The side error of A-Type is 7.058mm, which can cause changes to the design shape. The side error of B-Type is 21.377mm, which can cause changes to the design shape. Figure 6 shows this in colors. The + value is the amount of protrusion of the panel from the design shape, and it is shown in red. The - value is the amount of indention of the panel from the design shape, and it is shown in blue. (a) shows the error value of the A-Type panel in colors. Concrete placement quantity is concentrated more toward the bottom point of the curve based on the central axis of the produced panel. This is judged to be due to side pressure generated by the fluidity of concrete and the continuous free-form curves. (b) shows the error value of the B-Type panel in colors. The produced panel concentrates concrete placement in the center part. This is judged to be concrete not being able to spread and hardening due to internal molds produced using the wire mesh. In addition, it is judged that the side part had errors because concrete flowed to the wire mesh hole of the exterior molds produced using a metal lath.



(A) A-Type (B) B-Type

Fig. 6: FCP Error Measurement Result

5. CONCLUSION AND FUTURE WORK

With the recent growth in demand for free-form architecture, the importance of construction technologies is also increasing. Such free-form architecture has many limitations when constructing a massive exterior at once, and therefore, it is currently being customized by separating into multiple panels in sizes that can be produced. But during the course of this, many errors occur. In particular, errors in the joint areas between panels are directly connected to construction precision such as leading to leaks, etc., but the level of research on this is very low. Therefore, this study deduced the limitations of existing FCP side molds based on examination of preceding studies and developed a buried side molds as an alternative to make improvements.

Existing FCP side molds had limitations in that it was impossible to secure precise plastering sides structurally due to free-form curves. In addition, there were limitations in errors occurring in the panel because the side molds could not withstand the side pressure of concrete when not hardened. In order to make improvements to this, designs for A-Type molds that used a steel plate and B-Type molds that used a mesh wire were drawn up. The A-Type molds was designed using standard SUS steel plates and steel to secure sufficient strength to resist the side pressure of concrete and precise shape of the FCP side. B-Type molds reduced the use of steel compared to A-Type molds to secure economic feasibility while reducing weight, and it was designed with a wire mesh and metal lath. Buried side molds were produced based on these designs. Afterwards, in order to verify whether the produced molds satisfy the objective of this study, one-direction FCP panel production experiments were conducted, and it was scanned to analyze the error value.

In result, the error of A-Type molds that used the steel plate was 7.058mm, and it was analyzed that this was because the buried side molds could not withstand the side pressure generated by the fluidity of concrete or curves of the silicone plates on the bottom. The error of the B-Type molds was 21.377mm, and it was analyzed that this was because of the concentration of internal placing and concrete leaks on the outside. Therefore, such buried side molds require supplementation such as adjusting the thickness of the metal lath used during production of forms and editing fluidity of concrete used in FCP production.

The buried side molds developed in this paper is the first time for introducing the concept of burying among FCP molds production technologies that were researched in the past. It has sufficient value for research, and it is expected that the commercialization of this technology will lead to active use in developing domestic FCP production technologies.

6. ACKNOWLEDGEMENTS

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