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Development of an Adaptive Slicing Algorithm of Laminated Object Manufacturing Based 3D Printing for Freeform Formwork

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Abstract: Recently, as "Freeform buildings" have increased in number, studies on ways to increase productivity in the construction of freeform buildings are increasing. In the case of 3D printing in construction, many studies are being conducted using the material extrusion method; among the 3D printing methods, manufacturing freeform forms using laminated object manufacturing (LOM) can overcome the limitation presented above. However, there is a lack of cases used in LOM construction sites, so it is necessary to increase the productivity of construction work and study the slicing method suitable for construction. Therefore, in this paper, we propose using study criteria and adaptive slicing methods to combine both the shape error and the manufacturing time of freeform construction. A case study was conducted to verify the results of this study; the freeform concrete form manufacturing with the algorithm that proposed this study could save 66.1% of the manufacturing time compared with CNC milling, and it needs 19.8% less manufacturing time than the existing uniform slicing method. This is a result of the production of one freeform form, and it can be expected to have a greater effect if applied to many freeform forms used in construction sites. In addition, the results of this study can be used as a decision-making tool that can determine the shape and manufacturing time of production according to the on-site situation.

Keywords: 3D printing; slicing; laminated object manufacturing; formwork

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1. Introduction

The term "Freeform building" means a building consisting of walls, pillars, and ceilings, including free curved surfaces, rather than conventional vertical perpendicular members. A free curved surface refers to a complex, curved surface that cannot be represented by an analytical expression, unlike a regular shape, such as a circle, ellipsoid, or cone. In the case of the construction of a freeform building, since it is different from traditional circular columns and vertical walls, it is impossible to construct it via a traditional construction method [1]. To enhance the constructability of a freeform building or structure, it is important to make the corresponding formwork accurately, quickly, and cheaply [2]. In general, when constructing concrete buildings or structures, the cost of manufacturing and installing formworks is 40% to 60% of the total construction cost [3]. To accomplish this type of construction, various methods for the actual construction of freeform buildings have been studied.

In the case of fused deposition modeling (FDM), in which concrete mortar is squeezed out of a nozzle and stacked in layers, numerous studies have been conducted in connection with automated construction [4–6]. Since this method involves stacking in a direction perpendicular to the ground, there is an advantage in the construction of a curved wall that is perpendicular to the ground [7]. There is also a method of making a curved building using an expanded polystyrene (EPS) form spacer. It is a method in which an EPS form block is cut into a curved surface with CNC and inserted into the wood–steel form to form

a curved surface [8–10]. Since it is a method of precisely processing an EPS form block with CNC, a free curved surface spacer with very high precision can be manufactured. Making freeform objects or molds with LOM-type 3D printing has also been studied a lot [11–13]. Laminated object manufacturing (LOM) is a method of cutting a plate-shaped material into the desired shape and stacking it to make a 3D object. Compared to FDM, where the material is ejected from a nozzle and stacked in a line shape, LOM is processed by plates that have a larger area than the line. Studies have also been conducted on the method whereby the plate is cut by giving it a slope rather than cutting it at a right angle, which removes staircase effects and creates a smoother appearance [12,14,15]. In addition, studies on slicing, which is an essential element for additive manufacturing, are also being conducted. In particular, many slicing-related studies have suggested the concept of adaptive slicing and argue that applying adaptive slicing is better in shape accuracy and the total number of layers may be reduced than stacking with a uniform thickness. In the slicing phase, there is a study to apply the adaptive slicing concept by calculating the difference from the original model such as cusp height and staircase effect error [16–19]; there is also a study to calculate surface error using the concept of ruled surface [20–23]. In addition, depending on the shape of the structure, studies are being conducted to propose a method of partially cutting and fitting the shape for complex features with conceptual approaches of uniform slicing, adaptive slicing, local adaptive slicing, and region-based slicing [24,25]. In this study, the error calculation method of these preliminary related studies was referred to, but this study is about building construction different from the preliminary related studies, and the tolerance of error was applied more widely than them. In addition, this study applied a method of calculating surface error by converting the STL file into a lattice surface to make the error calculation more precise.

A method of judging and producing freeform molds based on LOM is required to elevate the esthetic, which is the essence of freeform buildings, and to attain high productivity, which is an important factor required for construction. It is possible to form a curved surface perpendicular to the ground by using the FDM method, but there is a limit to manufacturing a free curved surface that is curved, even in a direction perpendicular to the ground. This is due to the possibility that the stacked concrete may be separated or dropped if the slope of the curved surface changes rapidly or the member floats in the air. The spacer manufacturing method via CNC processing with high precision takes a long time because all volumes are cut through the end point of the tool. In terms of construction work, this means more precision and lower productivity than necessary. In the case of LOM with uniform slicing, more research is needed in terms of mold fabrication for the construction field. Furthermore, there is a limitation in that research on the adaptive slicing method with high-productivity construction work is insufficient.

In this paper, we propose judgment criteria and adaptive slicing methods to consider both the shape error and the manufacturing time for freeform construction. The adaptive slicing algorithm in this paper is a user-customized slicing algorithm because it has the ability for users to determine tolerances. In addition, the error in finding matching points is minimized because the original model is sliced by making a conversion to a file in the form of lattice without using the STL file, which is the most commonly used file. Firstly, the method of fabricating the LOM-type freeform building is briefly described. Secondly, we describe the method of calculating the shape error between the ruled surface and the original free curved surface in the process of cutting the plate in LOM. Next, we propose a determination algorithm that variably determines the thickness of the plate to satisfy a given tolerance of shape error. It was confirmed that adaptive slicing could reduce time by about 19.8%, even under similar shape error conditions, when comparing the uniform slicing LOM method via the manufacturing simulation to the test case. By manufacturing three EPS form spacers using CNC processing, uniform slicing LOM, and adaptive slicing LOM, we researched the advantages that adaptive slicing can have over other methods.

2. Methodology

2.1. Overview of the Fabrication of LOM Formwork and the Fabrication of Freeform Buildings

The construction method of a freeform building using the LOM method is shown in the Figure 1. The entire process consists of a phase of designing a building member and a 3D modeling of freeform form, a phase of manufacturing a form, and a phase of manufacturing Freeform using LOM and members using a freeform form. In this paper, as a core stage for manufacturing a mold, a slicing method that can consider both shape error and manufacturing time is proposed.

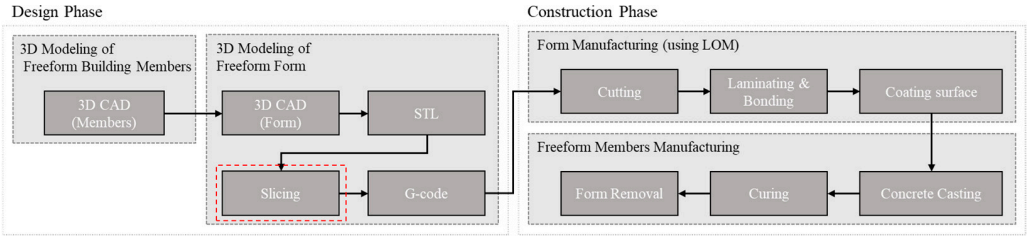


Figure 1. Overview of Fabrication Process for Freeform building.

2.2. Slicing

In order to manufacture a spacer for a mold or formwork through LOM, an object must be sliced into appropriate thickness with several layers, and each plate must be cut to form each sliced layer. The thinner the plate material, the smaller the difference from the original shape. However, as the length of the toolpath that needs to be cut increases, the process of cutting all of the layers and the process of attaching each layer increases.

(1) Shape error

Each layer can be formed by slicing one spacer according to a certain height; each layer has its thickness. Each surface of one layer can be represented by A_i and A_{i+1}, and the outermost curves forming the perimeter of each surface can be represented by R_i and R_{i+1}, respectively. A surface called a ruled surface can be newly formed through a linear line passing between these two curves. At this time, the two curves are also called the generator curves. As shown in Equation (1), the ruled surface S(u,v) formed from generator curves can be expressed by the following equation with respect to the following generator curves [22,23]:

$$\mathrm{S}(\mathrm{u},\mathrm{v}) = \mathrm{v}R_i(\mathrm{u}) + (1-\mathrm{v})R_{i+1} + 1(\mathrm{u}),\ (0 < \mathrm{u} < 1,\ 0 < \mathrm{v} < 1) \tag{1}$$

Since the ruled surface is a linear interpolation of an original surface, a shape difference occurs. As shown in Figure 2, a surface error (ε_i) can be defined as the maximum distance between the original surface and the ruled surface [22]. Since the interval between the original surface and the ruled surface is defined as a shape error, the smaller the e_i, the smaller the difference between the ruled surface and the original surface [22].

$$e_i = \frac{\overrightarrow{R_l l_j} \times \overrightarrow{R_l R_{l+1}}}{\left|\overrightarrow{R_l R_{l+1}}\right|} \tag{2}$$

According to the definition of the shape error (ε_i), in theory, the shape error can be calculated for infinite points on the generator curve. In a previous study, the shape error was calculated using the triangular facet of the STL format as a reference point [26]. As shown in Equation (2), in this paper, to easily calculate and analyze the shape error numerically, the original surface is converted into a lattice surface [27,28].

The lattice surface is a representation of a surface using a set of points; each point is derived from a grid that has a regular interval. From these points (i_j), a finite number of

shape errors (e_i) can be calculated since the shape error is the distance between the ruling line (R_iR_{i+1}) and these points.

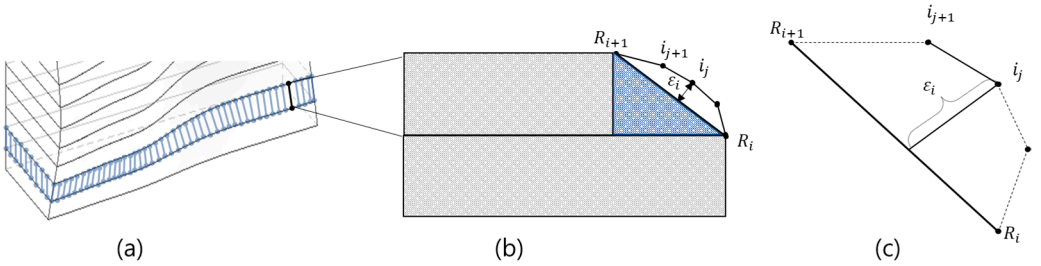


Figure 2. Schematic of the slicing; (**a**) generator curves and ruled surface; (**b**) cross-section with respect to a ruling line; (**c**) ruling line and surface errors.

(2) Thickness determination by the shape error

Where the thickness of a plate used in LOM varies, the thickness of the plate may be determined according to the criteria of surface error. Since the shape error of the regulated surface and the original surface is caused by the division of one spacer into layers, the surface error is automatically determined when the thickness is determined. In order to keep the surface error below the given tolerance, it is important to divide the spacer into layers of an appropriate thickness.

First, when the thickness of the plate used in the LOM is the same (uniform slicing), the thickness can be determined where the surface errors do not exceed the criterion. Since the thickness of the plate is constant, the supply and use of materials are relatively easy, but it is inefficient since the same plate must be used, even for a part where a thicker plate can be used. Secondly, the thickness of the plate material may be variably applied according to the surface error (adaptive slicing). In the case of EPS form, which is generally used in LOM, it is manufactured to a thickness of 5 mm or 10 mm, such as 10 mm, 15 mm, 20 mm, etc., so it can be determined according to the thickness. Starting with the thickest thickness, we can calculate the surface error, and if the calculated surface error exceeds the criteria, then we can move on to the next thickness. The spacing between the ruled line (R_{i+1}) and the thickness of the plate can be determined by not exceeding the surface error in the ruled line (R_i). This determination process is shown in Figure 3.

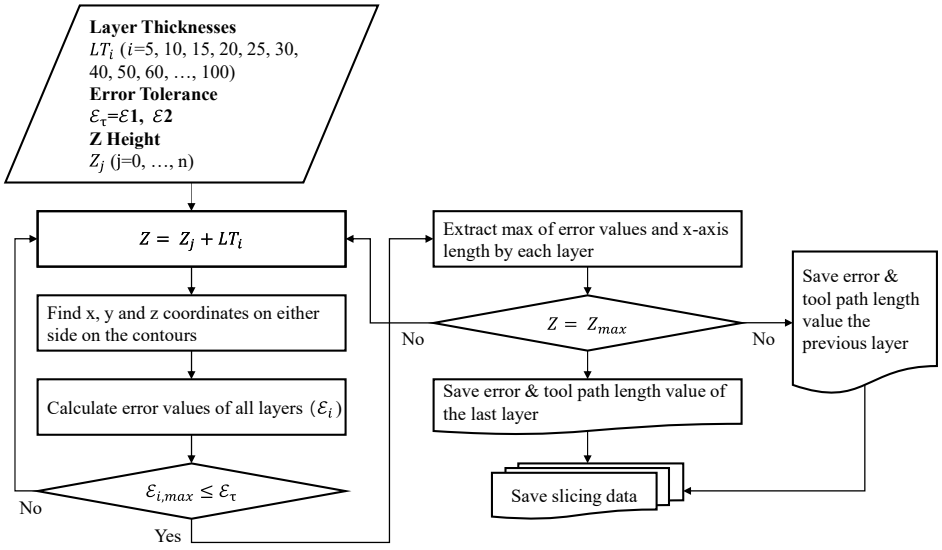


Figure 3. Determination process of layer thickness in the adaptive slicing.

(3) Calculation of production time

In the case of manufacturing a freeform formwork using LOM, the surface error (ε_i) and the time required for the manufacturing process must be considered. This is because precision in the construction process and the production time have an important influence on construction [29,30]. As shown in Equation (3), the time required to cut the EPS form panel can be calculated by the distance the tool end moves (L) and the speed of the tool end (C). The time required for the process of applying an adhesive can be calculated by multiplying the number of layers (n) by the time coefficient of applying it on one layer (a).

$$T = \frac{L}{C} + a \times n \tag{3}$$

3. Experimental Setups

3.1. Equipment for Cutting EPS Form Panel

As the cutting equipment for the production of the freeform formwork proposed in this study, a device that cuts the EPS panel with a CO_2 laser was developed as shown in Figure 4. Information on the equipment is shown in Table 1. The laser head featured is able to control the tilt angle as well as the parallel movement so the EPS panel can be cut according to an inclined shape [31,32]. The cutting equipment used in this study is an S-LOM type equipment developed through prior research. In this study, the laser output power is fixed at 60 W, but according to the preliminary study, the maximum output power is 75 W, and it is suggested that it can be used according to the situation by changing the size of the output power [31–33].

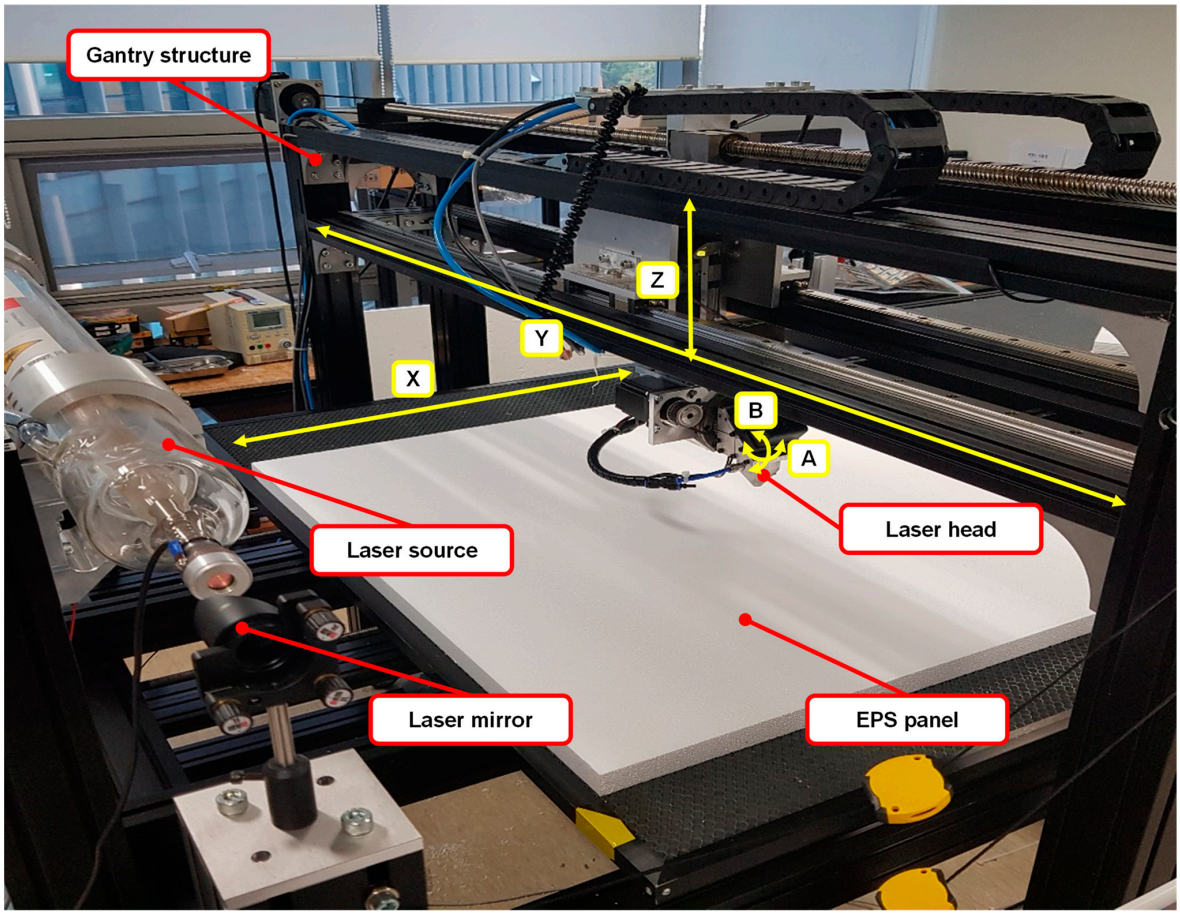


Figure 4. Laser based cutting machine of EPS panel.

Table 1. Information on the equipment.

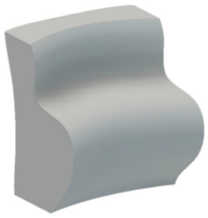
Items	Content
Laser type	CO_2 laser tube
Laser power	Max 75 W
Frame size (W × D × H) ※	1580 mm × 1400 mm × 1530 mm
Workspace (W × D × H) ※	1500 mm × 1320 mm × 100 mm
Cutting velocity	26.7~41.7 mm/s
Cutting range of angle	$-60° \leq \theta \leq 60°$

※ W = Width, D = Depth, L = Length.

3.2. Target, Simulations, and Actual Fabrication

The bench of Waterpark City in Toronto, Canada [34], was selected as a target to study the surface error and process time. The target was selected because it was suitable for examining surface errors along the original freeform surface, including both convex and concave slopes. The test case was 600 mm wide, 600 mm long, and 660 mm high, which was simplified to select an area corresponding to the width of a wood–steel form (600 mm × 660 mm). Information on the target is shown in Table 2.

Table 2. Description of case project.

Items	Contents	Design (One of Module)	
		Bench	Form
Project name	Waterpark City Freeform bench		
Material	Concrete/EPS		
Number of modules	28		
Size (W × L) ※	600 mm × 660 mm		
Angle of tangential plane	$5° \leq \theta \leq 120°$		

※ W = Width, L = Length.

A total of seven simulations were conducted on the target case proposed above. In the case of uniform slicing, there were five cases, which had a height of 10 mm, 15 mm, 20 mm, 30 mm, and 60 mm. The other two cases involved the adaptive slicing method, with the surface error standard (e_t) of 2.0 mm and 5.0 mm.

In the case of uniform slicing with a thickness of 30 mm, adaptive slicing with surface error criteria (e_t) of 5.0 mm was selected and manufactured. The time required for the process of cutting, attaching, and stacking EPS plates was measured. The shape error was measured by laser-scanning the manufactured mold using stereoSCAN neo equipment [35].

4. Results and Discussion

4.1. Simulation Results

The surface error (ε_i) calculated in the simulation is represented according to the height of the target shape, as shown in Figure 5. At the height where the generator curve (R_i) is located, the surface error (ε_i) is zero because the ruled surface and the original surface match each other. As the height of the generator curve increases, the shape error increases, and as the height rises again, the shape error gradually decreases and appears to reach zero.

In the case of uniform slicing, it may be seen that a relatively large shape error occurs near a position (height of 400 mm), where the radius of curvature is small, and the angle is greatly changed (height of 400 mm) because the thickness is constant. The maximum error is 9.67 mm and 25 mm for thicknesses of 30 mm and 60 mm, respectively.

In the case of adaptive slicing, the height is determined so that the shape error by the rule surface is less than or equal to the criteria (e_t), and, thus, it is 2 mm and 5 mm or less, which is the tolerance in all ranges.

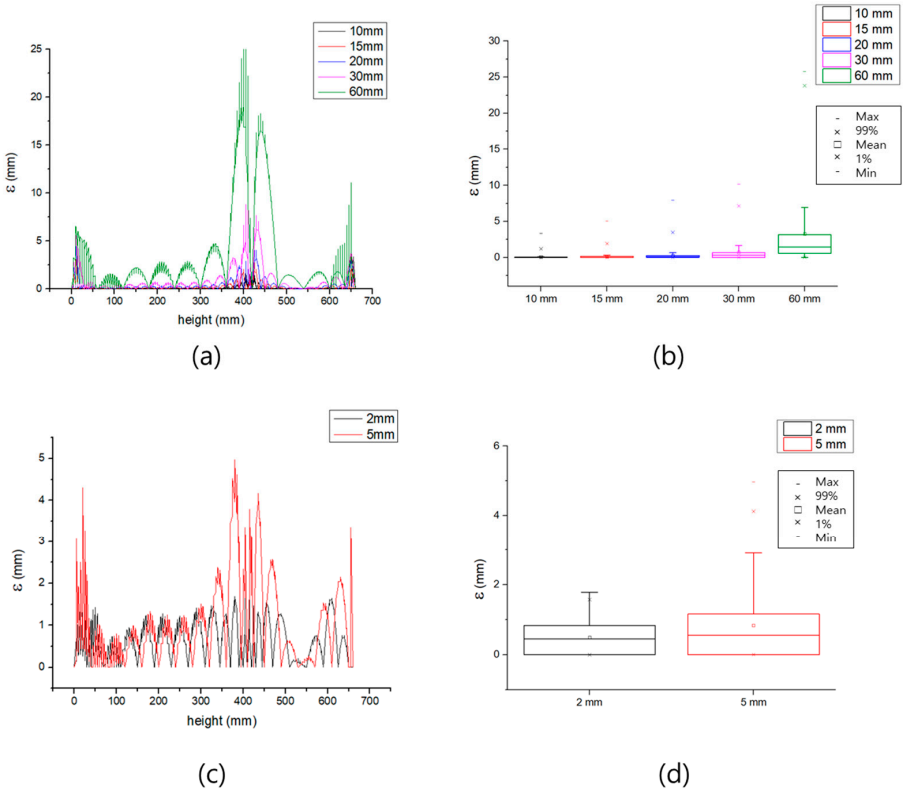


Figure 5. Graphs of the simulation results; (**a**) surface error of uniform slicing with respect to the height; (**b**) box chart of surface error of the uniform slicing; (**c**) surface error of the adaptive slicing with spec to the height; (**d**) box chart of surface error of the adaptive slicing.

The simulation results, including the shape error (ε_i) and the production time (T), are shown in Table 3. In this paper, the speed of the laser head (C) was 6 mm/s, the adhesive application time of each layer was 45 s (a), and the minimum manufacturing time was calculated by these coefficients. In the case of uniform slicing, as the thickness of the panel increases, the number of plate materials decreases, the toolpath length decreases, and the time required for cutting decreases sharply. In addition, as the thickness of the plate increases, the maximum error also increases rapidly. In the case of adaptive slicing, the number of layers was formed according to the allowable shape error (e_t). Comparing only the average shape error and the standard deviation of the shape error for the target feature, the cutting situation with a 2 mm adaptive may look similar to the value between 20 mm and 30 mm thickness, but both 20 mm and 30 mm show an incomparable error value. The time required is also shorter in the 2 mm adaptive method. As a result, the shape error and estimated time generated through the above simulation were taken into account for the test case in this research, and it is expected that it will be used as basic data to utilize LOM and to select the thickness of EPS form suitable for the construction site.

Table 3. The simulation results.

	10 mm Uniform	**15 mm Uniform**	**20 mm Uniform**	**30 mm Uniform**	**60 mm Uniform**	**2 mm Adaptive**	**5 mm Adaptive**
Number of layers	66	44	33	22	11	20	15
ε mean (mm)	0.0535	0.1391	0.2751	0.7128	3.2798	0.4973	0.8363
ε standard deviation	0.1802	0.3314	0.5853	1.3770	5.1956	0.4696	0.9721
ε maximum (mm)	3.3541	5.0596	7.9131	10.1825	25.7666	1.7848	4.9684
Tool path (mm)	41,837	27,841	20,890	13,951	7014	12,712	9522
Cutting time (min)	116	77	58	39	19	35	26
Plastering time (min)	49.5	33	24.75	16.5	8.25	15	11.25
Curing time (min)	90	90	90	90	90	90	90
Minimum manufacturing time (min)	256	200	173	145	118	140	128

4.2. Experimental Results from Production

For actual manufacturing, a uniform 30 mm thickness and an adaptive slicing case with a 2.0 mm tolerance were selected. The conditions and actual fabrication shapes are shown in Figure 6. The error obtained by measuring the actual production result with a measuring instrument and the time required is shown in Table 4 and Figure 7. In Figure 7a is a criterion for comparing each subject with an existing 3D model, and the models of Figure 7b–d are overlapped with Figure 7a to express the error in color. The closer the color revealed in the three comparison models Figure 7b–d is to green, the less the shape error is, and the larger the shape error is to red and blue. According to the experiment, in the case of CNC processing, the average value of shape error was the lowest, and the error increased in the order of adaptive and uniform slicing. However, in the middle of the area where the EPS itself is weak due to its thinness, there is a limitation in that all three cases show a maximum error of more than 10 mm. However, in Figure 7d the maximum error of adaptive slicing is shown to be the smallest, and 16.6693 mm is not a significant influence on construction, so it is considered suitable for freeform building construction. There were more errors than the simulation results because there was an additional manufacturing error caused by the actual processing and manufacturing of the wood–steel form.

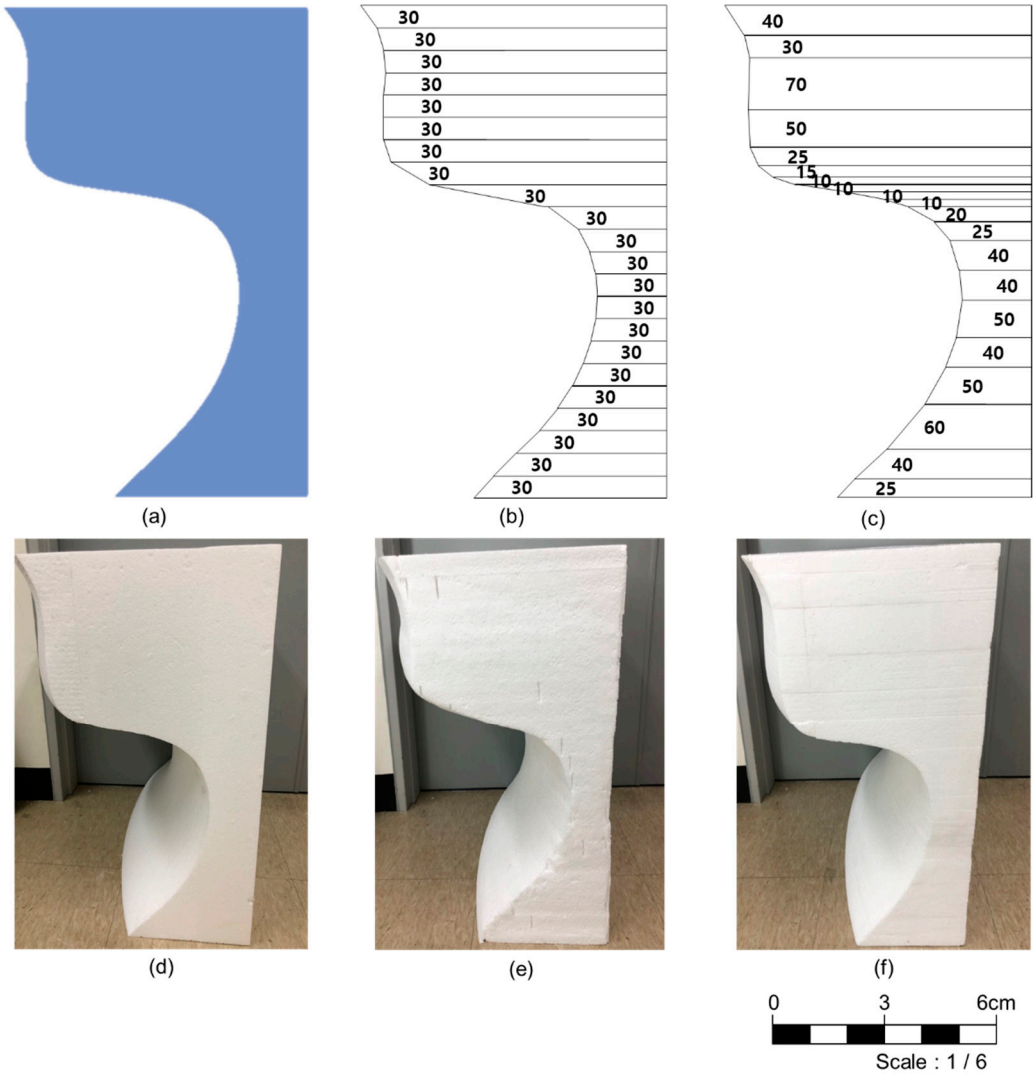


Figure 6. Schematic and picture of manufacturing results; (**a**) Original shape (side); (**b**) uniform slicing by thickness of 30 mm; (**c**) adaptive slicing with error tolerance (e_t) of 2 mm; (**d**) CNC milling; (**e**) uniform slicing; (**f**) adaptive slicing.

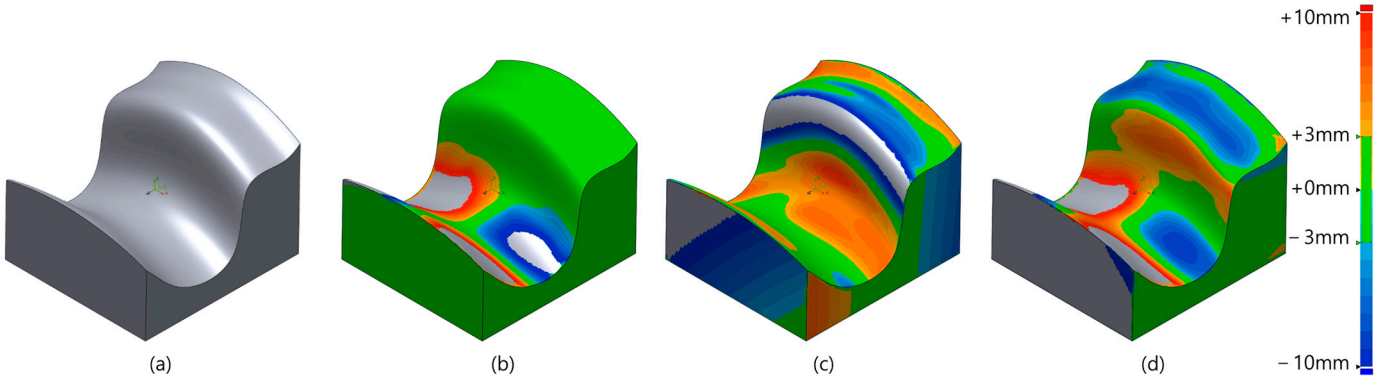


Figure 7. 3D Contour graphs of surface errors; (**a**) target surface; (**b**) CNC milling; (**c**) uniform slicing; (**d**) adaptive slicing.

A flattening process (sanding) is additionally involved since, due to the characteristics of the laser-cutting of 3D printing equipment, a melting cross-section between the part to which the laser is directly irradiated and the EPS plate is discharged is different, and a burr occurs in the process of cutting a thick EPS panel. In terms of the total time required, including all processes, the CNC method took the longest at 348 min, uniform slicing took 158 min, and the adaptive method took the least amount of time at 151 min. The simulation of the uniform process used 30 mm and 2 mm because the number of layers was similar in the first place, the time required was similar in actual production, but the adaptive was advantageous, and the shape error was incomparably advantageous.

Table 4. The error obtained by measuring the actual production result with a measuring instrument and the time required.

	CNC Milling	Uniform Slicing	Adaptive Slicing
Number of layers	-	22	20
ε mean (mm)	−0.2886	−3.5438	−1.6529
ε standard deviation	2.0419	6.0466	4.0424
ε maximum (mm)	21.6269	20.5244	16.6693
ε minimum (mm)	0.0021	0.4130	0.0917
Cutting time (min)	348	39	35
Plastering time (min)	-	17	15
Curing time (min)	-	90	90
Sanding time (min)	-	12	10
Total manufacturing time (min)	348	158	151

4.3. Discussion

The slicing algorithm developed and presented in this study affects the productivity of mold production required for the construction of freeform buildings.

This study developed and proposed an adaptive slicing algorithm suitable for applying 3D printing technology to freeform building mold construction. In this research, unlike existing studies [17–23] that verified the adaptive slicing algorithm only by simulation, comparative verification was performed through case study after simulation. In addition, the thickness of the layer was determined one by one because existing studies calculate the cusp height assuming the original surface as the arc when applying adaptive slicing. This is similar to the use of tolerance in this study as a method of maintaining the cusp height below the criteria [20], but the limitation is that the original surface is simplified into the arc. In addition, the adaptive slicing method of the existing study is to narrow the error below 0.1 mm, but this is difficult to apply when the original surface has two or more curvatures [17–19]. On the other hand, in this study, since the thickness of the layer is determined by applying the concept of ruled surface, it is suitable for freeform rather than

simple arcs. Since this study targets building construction, the value of tolerance is greater than that of other studies. In addition, applying adaptive slicing concepts such as local adaptive slicing, region-based slicing, and feature-based slicing to partially fabricate and combine complex features [24] may not be suitable for productivity-focused construction. The existing studies have performed adaptive slicing based on STL files, but STL files of freeform models can be found to have many errors, and many tasks to correct them can occur [21,22]. Therefore, in this study, converting to a latticed file was applied to minimize errors in the STL file and optimally find the matching point.

The results of this study are characterized by the fact that the amorphous formwork production method can be determined in consideration of the time, cost, and precision of shape according to the background, conditions of the project, and the requirements of the contractor. This characteristic will help the contractor make a reasonable plan and implement the project because it helps to make decisions on the amorphous form production method under various conditions in consideration of the preceding and following processes as well as the simple form production stage. In addition, the adaptive slicing algorithm presented in this study is not limited to the production of amorphous building molds but can also be used in the design stage of 3D-printing-based sculpture production.

This study not only proposes a criteria and determination process but also an adaptive slicing algorithm to utilize the freeform formwork production through LOM. However, the total mold production time was calculated as the average value of the author's experimental data, such as setting the mold included in the final mold production time and the time for subsequent tasks, such as sanding (surface treatment). In future studies, it is necessary to approach the time of preceding and following work probabilistic through multiple experiments under various conditions. In future research, a slicing algorithm is also needed to install a mold made to suggest a more accurate mold-making decision and to consider whether the surface shape may be deformed or the mold may be damaged due to lateral pressure when placing concrete. To achieve this, it is necessary to develop the slicing algorithm in consideration of the shape, time, and variables in the working stage by manufacturing various cases using this algorithm. An upgrade of S-LOM equipment will also be required. The thickness of the EPS panel shall be variously prepared to produce forms by applying the slicing algorithm proposed in this research, and an automated system in which the EPS panel could be arranged should be established to take charge of the result. In addition, future research is needed so that a system capable of optimally selecting and outputting an output size of a cutting laser suitable for the thickness of an EPS panel can be constructed together.

5. Conclusions

This paper proposes a method to consider shape errors and the production time of form making for efficient manufacturing of freeform forms used in building formwork using laser cutting S-LOM equipment. This method was also analyzed through simulation and actual production. The conclusions are as follows:

1. This algorithm calculates the error of the ruled surface that is cut by the shape and the printer that is intended to be produced. It also suggests the range of tolerance according to the type of freeform building components, estimating the optimal alternative for freeform concrete form manufacturing.
2. According to the simulation results, in the case of a method of uniform slicing or constant thickness, there was no method to control or prepare the shape error. In the case of uniform slicing, a shape error of up to 25 mm occurs in a sharply curved part around 400 mm in height with respect to the test case, which is not suitable in terms of the esthetic nature of a freeform structure, and it is expected to cause undesirable effects on stronger curved shapes.
3. For comparison, the target shape was also created by CNC milling. CNC milling was very good in terms of precision, but the average error of 0.2886 mm is too high

of precision for construction sites, and it takes an overwhelming amount of time to remove this error.

4. In the case of actual fabrication with respect to 30 mm uniform slicing, there was a severe error on the curved surface. When it comes to adaptive slicing with 2.0 mm criteria, the surface error is expected due to the processing error but is allowable in terms of the construction site.
5. The time required was almost the same due to the similar number of layers in the adaptive process, but the time required was 151 min, even though the shape error was limited and lessened. There was this much difference in the test geometry conditions—only 600 mm by 600 mm with a height of 660 mm—but the difference would be very large when expanded to the entire wall and building.

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