Rationalization of Free-form Surface Construction Method using Wooden Formwork

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Abstract –

In Japan's construction industry, techniques of producing complex three-dimensional (3D) formwork at construction sites are conventionally developed using the sophisticated skills of carpenters. Inspie of the development of digital technologies, the production of free-form shapes faces considerable cost and time management risks that require pragmatic solutions. In the efficient building of free-form shapes, the continuous surface should be divided into portable elements for formulating production plans and for making products in the factory. The products should then be installed and assembled at the construction site. Hence, new methods with computational design are assumed to require an approach different from the traditional processes of designing and constructing with two-dimensional (2D) drawings.

This research aims to analyze the productivity of these conventional means and propose a New Method of constructing free-form formwork for real-scale buildings.

First, we focused on how the designed geometric coordinate information is translated for construction on complex wooden formwork. We revealed how these shapes were realized by carpenters, and organize cases from 1991 to 2020 to see how the existing Japanese wooden formwork technology can realize double-curved surfaces.

Second, we focused on a completed project that has a 5,100 m^2 free-form RC roof constructed using the nonuniform rational B-spline (NURBs) curve and conventional production methods. Additionally, we analyzed the project's production time and cost from the construction records and revealed that the methods heavily depended on on-site labor.

Finally, based on the analysis results, we propose a production method in which curved surfaces are divided into portable units to reduce on-site labor and ensure high accuracy. We also analyzed its productivity through some assembly experiments. The labor cost of the New Method is lower by 93% than that of the existing method.

Keywords –

free-form structures; 3D CAD; wooden formwork; labor productivity

1 Introduction

1.1 Background and purpose of the study

In Japan's construction industry, techniques of producing complex three-dimensional (3D) formwork at construction sites are conventionally developed using the sophisticated skills of carpenters [1]. The development of digital technologies, especially 3D computer-aided design (CAD) and 3D structural analysis, has recently facilitated the design of even free-form shapes. However, the production of such free-form shapes still has considerable risks in cost and time management. In addition, in recent years, it has become difficult to maintain these skills due to Japan's aging population and shortage in carpenters. These problems require pragmatic solutions. To build free-form shapes efficiently, one should divide the continuous surface into portable elements for formulating production plans and for making products in the factory. The products should then be installed and assembled at the construction site. Hence, new methods with computational design are assumed to require an approach different from the traditional processes of designing and constructing with two-dimensional (2D) drawings. Creating complex and continuous shapes on the architectural scale requires considerable time and money, given the need to adjust the details of each part and assemble them at the construction site.

This study aims to develop a construction method that optimizes productivity throughout the building process—from design to on-site-assembly—by combining digital fabrication with conventional wooden construction techniques on the actual building scale. This study focuses on methods in the Japanese construction industry and assumes the proficiency and costs of labor to be those in Japan.

1.2 Methodology

First, we analyze and organize cases after the emergence of CAD to see how the existing Japanese wooden formwork technology can realize double-curved surfaces, which are difficult to reproduce with wooden formwork. Second, we examine the current situation of free-form shape production by surveying an example of a free-form reinforced-concrete (RC) roof construction project that was realized using conventional construction methods in Japan and nonuniform rational B-spline (NURBs) surfaces, which have become a mainstream method for describing 3D geometries since the 2010s. And we analyzed the time and cost of its construction process. Third, we developed a production method in which curved surfaces are divided into portable units to reduce on-site labor and ensure high accuracy. Fourth, by analyzing and comparing the time, cost, and shape reproducibility of the new method with those of the conventional construction method, we offer an ideal method of constructing free-form buildings.

2 Classification of construction methods of wooden formwork with double-curved surfaces

2.1 Classification of construction methods

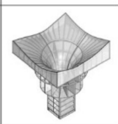
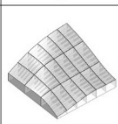
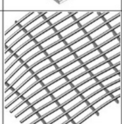
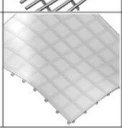
In the classification in the graphic science, curved surfaces can be divided into two typologies: ruled and double-curved surfaces [2]. A ruled surface, such as a cylinder or hyperbolic paraboloid surface, can be defined as a linear trajectory that moves smoothly with a one-degree-of-freedom parameter. This type can be further classified into single-curved surfaces, such as columnar and conical surfaces, and warped surfaces, such as bipolar parabolas and spirals with torsion. Because these curved surfaces can be considered an accumulation of straight lines, they have been used in architectural design since the 1960s before the advent of CAD. By contrast, a double-curved surface does not have such a linear element and is thus difficult to regard as an accumulation of linear elements. In particular, free-form and double-curved swept surface shapes are difficult to accurately define in two-dimensional drawings. Around 1990, CAD began to penetrate the field of architectural design and has since made it possible to construct such surfaces.

In this study, buildings with double-curved surface RC elements constructed using wooden formwork were selected from issues of the most widely read monthly architectural design magazine in Japan, Shinkenchiku, published between January 1991 and May 2020. The number of buildings extracted was 72. Formwork methods for double-curved surfaces described in the magazine and other materials can be categorized into the following (Table 1).

(1) Small unit
(2) Radial unit
(3) Rectangle unit
(4) On-site construction: beams and joists
(5) 3D grid

(1), (2), and (3) are supposed to be made in the factory and assembled or joined on-site to make a larger surface. (4) and (5) are based on on-site production, and the use

Table 1. Classification of construction methods for double-surface formwork

	Figure	Method	Structure	Characteristics of the method	Sheathing board	Cases	Number
1		Small unit	Wooden ribs/foam	-Method for small objects, columns or slab edges	Narrow cedar boards	OMOTESANDO KEYAKI bldg.	1-c
2		Radial unit	CNC cut wooden ribs	-Method for surfaces close to the rotating shape -Often be made as fabricated unit	Veneers lamination	Kawaguchi city "Meguri-no-mori Crematorium in Kakamigahara	2-a
					Narrow boards	Yaoko Kawagoe Museum	2-c
3		Rectangle unit	CNC cut wooden ribs	-Method to make large curved surfaces by joining factory-produced square units in the construction site	Veneers lamination	Kawaguchi city "Meguri-no-mori Hokkaido-Daikannon	3-a
					Hot pressed board	Inamori Hall, Kagoshima Univ.	3-b
					Flexible plywood	Gokayama-Seikatsukan Science Hills Komatsu	3-d
4		On-site construction: beams and joists	Beams:CNC cut boards, Square timbers	-Method based on on-site assembly of beams, joists and sheathing board	Narrow boards	Crematorium in Kakamigahara Kawaguchi city "Meguri-no-mori	4-c
			Joists:Narrow boards		Flexible plywood	Island City Central Park "GRIN GRIN" Ginan Town Hall	4-d
5		3D grid	Square timbers	-Method to assemble bending wood or bamboo on a grid with rotatable joints	Fabric	Uchiho Community Center Naiju Community Center Kumamoto Ashikita Youth Center	5-e

of digital fabrication at factories is limited to the cutting of parts according to CAD data or on-site positioning.

According to how the sheathing plates are generated, construction method are further classified into the following categories.

(a) Thin veneer lamination
Three or four layers of thin and narrow veneer (3 mm) strips are laminated and glued to create a cylindrical shape with a large curvature.
(b) Hot press
Multiple laminated veneers with adhesive are heated and pressed against the male and female molds. Since the structure is made from a single plate, a seamless surface can be made with high accuracy.
(c) Use of narrow boards
Cedar or plywood strips with a width of 100–300 mm are fastened to joists (method (4)) on-site. Although the surface that can be reproduced is not as large as those in (a) and (b), it is easy to work on and can be assembled at the construction site.
(d) Use of flexible plywood
This is mainly employed in conjunction with (3) and (4). Flexible plywood is used and can be applied according to the shape of the small curvature surface.
(e) Use of fabric material
Fabric is used as a sheathing plate that needs to be followed by the movement in accordance with method (5).

Next, we explain the characteristics of each method (1)–(5) combined with the sheathing board method (a)–(e) with several case studies. Explains of These cases are based on construction plans prepared at the construction phase, or construction reports published in magazines.

2.2 Small unit

Small-scale units are used for the formwork of specially shaped elements, such as columns and slab edges. In ”OMOTESANDO KEYAKI bldg.”, designed by Norihiko Dan, each outer pillar is inclined and twisted, so the cedar board for finishing was glued to the foam that was hollowed out along the column’s outlines (1-c) [3].

2.3 Radial unit

For curved surfaces whose shape is close to rotating or convex shapes, the frame of the formwork is assembled radially. Radial structures are difficult to assemble at construction sites, so smaller ones are often made into units. In “Kawaguchi City Meguri-no-Mori” designed by Toyo Ito, the radial units were applied in a 2.6 m x 2.6 m area of the large curved column section. Sheathing plates consisting of four layers of 3 mm-thick veneer strips were affixed to the rib structures (2-a). Since the bottoms of the pillars gradually thin, the veneer was applied by twisting to follow the narrow cylindrical shape. Since the columns are 3–5 m high, they were divided into three sections and assembled at the site [4].

2.4 Rectangle unit

Large curved surfaces are made by joining factory-produced square units side by side on a grid to shorten the work at the construction site and ensure shape accuracy. In Japan, 1820 mm × 910 mm plywood board is common; the units are often made in a size of about 1.8 m × 0.9 m or 0.9 m × 0.9 m, with ribs lined up at a pitch of about 300 mm or 450 mm to create a guide for the shape. In the construction of the Gokayama Seikatsukan roof, designed by Elias Torres, the formwork was divided into 1,700 mm × 850 mm units (3-d) [5]. In the construction of Hokkaido’s Daikannon, a large RC Buddha sculpture designed by Ishimoto Architectural & Engineering, a scale model created by a sculptor was used to measure coordinates by physical contact, and a ring-cut model was made in the height direction. Based on these coordinate data, the shape between the contour lines was reproduced by carpenters by bending cedar and veneer boards (3-c) [6].

2.5 On-site construction: beams and joists

This method is based on the on-site assembly of the formwork, wherein beams, joists, and sheathing plates are placed on support pipes. For the roof of Building for Island City Central Park “GRIN GRIN”, designed by Toyo Ito, square timbers were used as beams for the small curvature of the roof; they were poured over the supports and then attached with plywood.

Square timber beams were pulled from the bottom with a turnbuckle to recreate the shape of the model at the site (4-d) [7]. However, this method was not able to achieve the expected level of shape accuracy. Based on this experience, steep and precise formwork was realized at the Crematorium in Kakamigahara (designed by Toyo Ito) by using CNC (computer numerical control)-cutting beams and layering a few layers of 12 mm-thin cedar boards on them to make flexible and strong joists (4-c) [8].

2.6 3D grid

This method was used in the 1990s to assemble bending wood or bamboo on a grid with rotatable joints. At the Naiju Community, designed by Shoei Yo, bamboo cage-like surface materials were assembled on a flat ground, and the roof’s shape was created by adjusting the shape of the cage over props. The sheathing board is made of fabric material; the shape can be adjusted on-site.

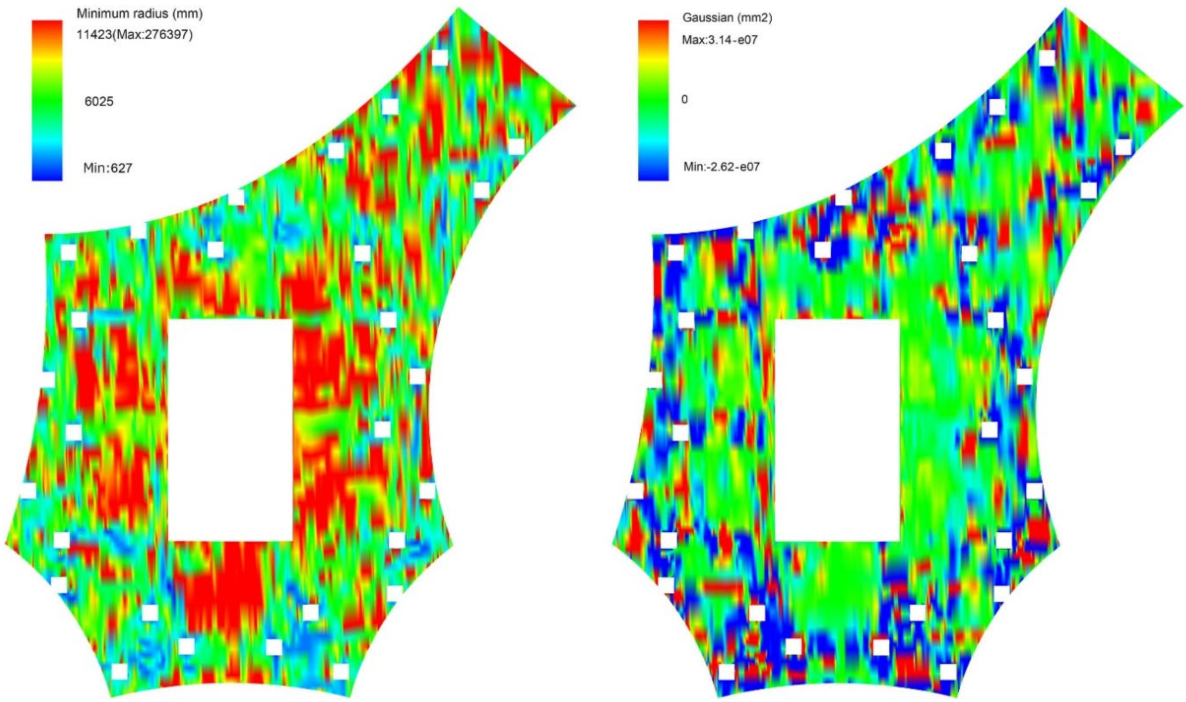


Figure 1. Minimal curvature and Gaussian curvature distributions on roof surface of Kawaguchi project

The fabric and bamboo were left behind after the concrete was poured to become the finishing material [9].

2.7 Summary

In Chapter 2, we classified construction methods for frames and sheathing plates for double-surface formwork. Each method is employed according to the shape of the curved surface, and all of these methods depend on-site work and the skills of formwork carpenters. The choice and combination of methods depend largely on the experience of formwork fabricators and carpenters. There are no previous studies comparing the productivity, shape accuracy, and price of these techniques or optimizing these methods.

3 Analysis of productivity of conventional construction methods

3.1 Outline of example of free-form RC roof formwork constructed with conventional methods

We focused on a completed project which has 5,100 m^2 free-form roof made from a 200 mm-thick RC slab using a conventional formwork construction method. We analyzed the production time and cost of the method from the construction records of the general contractor and found that the method heavily depend on on-site labor. The target is “Kawaguchi City Meguri-no-Mori” (hereafter the “Kawaguchi project”), designed by Toyo Ito & Associates, Architects and Sasaki Structural Consultants. The curved roof is supported by concrete-covered steel columns, and the shell structure was designed with computational morphogenesis (Fig. 1).

For constructing the main part of the roof, a method was adopted to build a curved formwork, with hand-bent joists and sheathing built on-site and installed with machine-cut beams. These beams were bridged on telescopic steel props placed on a Japanese traditional module grid measuring 915 mm. Each joist on the beams comprised four layers of 12 mm-thick pine strips (100 mm wide), and sheathing (also made from 12 mm-thick pine strips) was bent and installed manually at the construction site (hereafter the “Kawaguchi method,” 4-c, Fig. 2) Box forms (2-a, 3-a, 3-c) were adopted for the areas where the curvature changes abruptly (columns and roof edge) [4]. This chapter retrieves and analyzes productivity and shape accuracy data from the construction records of the Kawaguchi project’s general contractor.

3.2 Analysis of production time

In this project, on-site formwork production lasted from November 2016 to May 2017. A total of 1,883 man-days over 136 working days, excluding holidays, were needed for producing the curved roof formwork. On average, 13.8 people were working each working day,

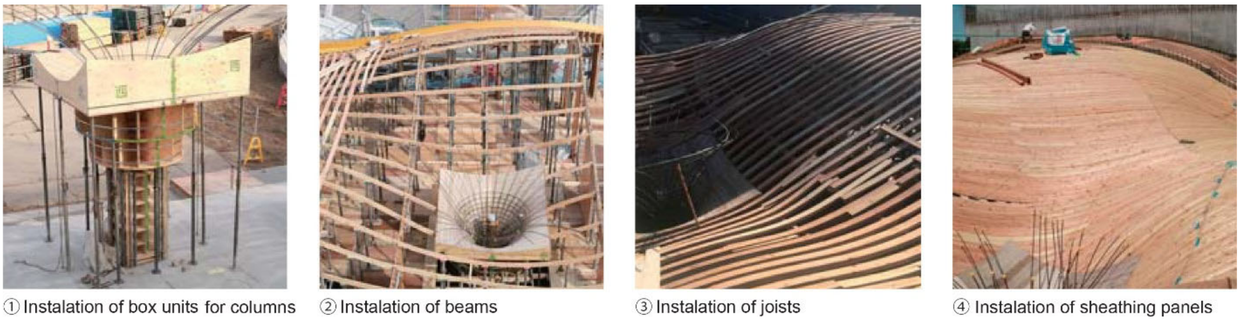


Figure 2. Work procedure of formwork for Kawaguchi project's free-form roof

with a maximum of 33 man-days. The man-hours at each stage of the formwork's installation in the main part of the roof are shown below.

1. Placing temporary supports: 408 man-days
2. Installing beams: 192 man-days
3. Installing joists: 320 man-days
4. Installing sheathing panels: 320 man-days
5. Adjusting levels and fixing: 288 man-days

Each laborer in this set of data worked eight hours a day, and the areas analyzed included the curved roof, the columns, and the joints between the roof and the wall, totaling 5,112 m^2. The total working hours of these stages were 1,528 man-days, and the average working time per construction area was 2.39 man-hours/m^2.

3.3 Shape accuracy analysis

In this construction project, before the concrete's placement, the general contractor measured the height coordinates of each point on the formwork's surface just above the prop with a light wave rangefinder. The prop's height was adjusted whenever there was a difference of more than 20 mm between the height of the formwork and that of the 3D model.

Because the top of the glass curtain wall's mullion was in direct contact with the concrete slab, the construction manager had to carefully manage the height of each contact point. Therefore, every month following the removal of the formwork, the roof slab's height was measured at each of the 153 mullion locations, and these data were fed back to the mullions' production length. Creep or deformation of the concrete slab was expected in the long-spanning area. Thus, the heights of several points in the middle of the span were also measured, and height displacement was checked to prevent any sudden transformation.

The data showing the height of these points immediately after the formwork's removal can be used as a data sample that shows the shape accuracy of the formwork at arbitral points on the surface. Fig. 3 shows the distribution of the height error for each measurement point.

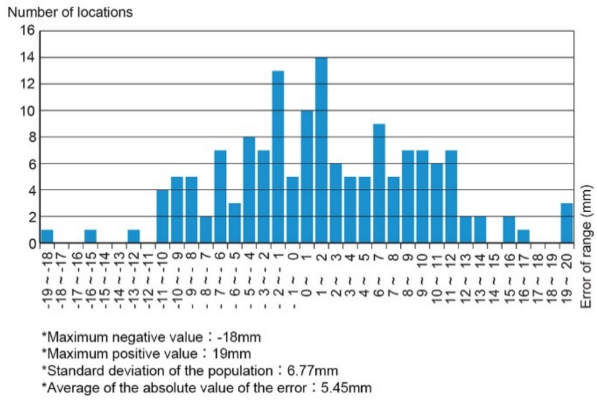


Figure 3. Distribution of height error of form

Table 2. Details of calculation of construction costs for Kawaguchi method's formwork

	Specification	Unit	Unite price(JPY)	Units per square meter	JPY/㎡	Calculation basis of unite price
material cost						
Machine-cut beam	h=100mm・double side / 915mm pitch	m	1,000	1.092 pieces/㎡	1,092	interviewes
Joist	75mm×t13mm×300mm pitch×4layers (4m length)	pieaces	500	3.3 pieces/㎡	1,650	interviewes
Sheeting panel	75mm×t13mm (4m length)	pieaces	500	2.79 pieces/㎡	1,666	interviewes
Telescopic steel props		pieaces	2,000	1.31pieces/㎡	2,620	the construction estimation standard [10]
Beam setting material		pieaces	170	1.31pieces/㎡	222	the construction estimation standard [10]
Square timber for bottom		㎥	33,000	0.032㎥/㎡	1,069	the construction estimation standard [10]
Prop joint connector		pieaces	1,890	0.76 pieces/㎡	1,436	the construction estimation standard [10]
Fixing clamp tool	150 days rental	pieaces	600	2.621pieces/㎡	1,575	interviewes
Fixing chain	150 days rental	㎡	400	1	400	interviewes
labor cost	2.39 man-hour/㎡	man-hour	3,075	2.39 man-hour/㎡	7,349	the construction estimation standard[10]
Total					19,079	(JPY/㎡)

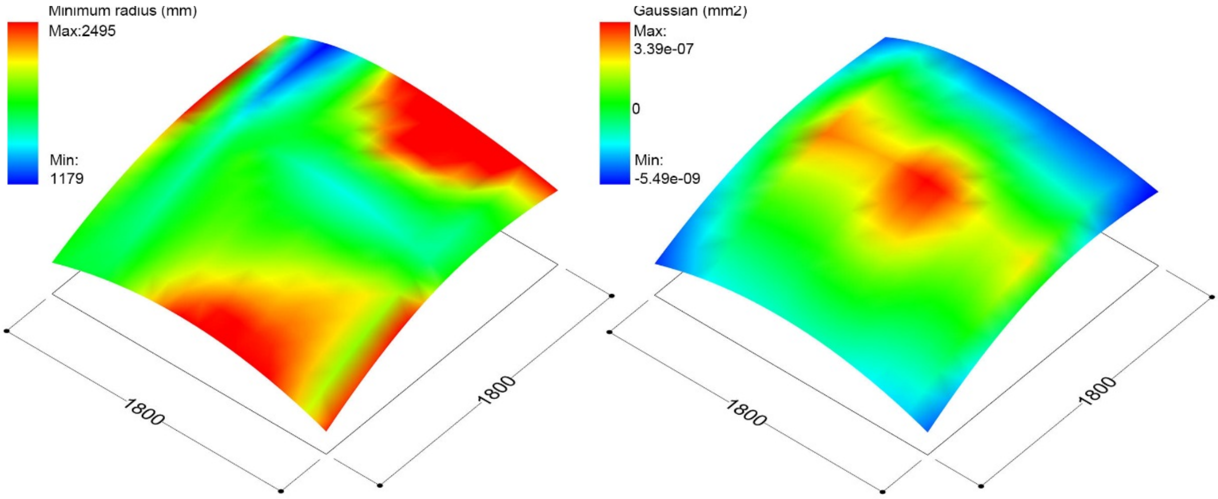


Figure 4. Minimal curvature and Gauss curvature distribution of target shape of new method's experiment

3.4 Cost analysis

We also calculated the cost per square meter of constructing the Kawaguchi project's formwork. The amount of material required to produce the formwork was calculated based on the project's construction plan papers.

We consulted periodically published standard construction estimation books [10] to find unit prices for each material, and asked contractors to fill in the missing data. The labor cost per square meter was calculated from the man-hours calculated in 3.1. The sum of the material and labor costs was regarded as the construction cost. Table 2 shows the process of calculating the total construction cost, which was 19,079 JPY/m^2.

4 Development of new unit construction method

4.1 Outline of new method

The cost analysis in Chapter 3 shows that labor costs account for 39% of the total construction costs, while the time taken to place temporary supports accounts for 27% of the total on-site assembly time. The time taken on-site to laminate five layers of a 100 mm-thick narrow board (joists and sheathing plates) accounts for 42% of the total construction time.

Therefore, in this chapter, we develop a new formwork method (hereafter "New Method") that uses factory-manufactured units to minimize on-site labor and reduce total costs. New Method proposes a way to use factory-manufactured 900 mm × 900 mm units instead of bending and assembling wooden boards at the construction site. It uses a rigid unit to reproduce surfaces with various curvatures (3-c). This system makes it possible to select a method for generating curved surfaces by matching the curvature of each part by dividing the surface into units. The overall cost and time required to construct the whole formwork are also optimized.

The experimental formwork units comprise a folding support system and a bent wooden sheathing panel that is reinforced by curved beams cut by CNC machines. Both the support unit and the sheathing panel can be manually operated by two laborers. Each part is manufactured in a factory and then assembled and fixed at the construction site to create an architectural-sized formwork with a free-form roof surface.

4.2 Outline of analysis subject

4.2.1 Sample shape

We extracted a sample shape measuring 1,800 mm × 1,800 mm from Kawaguchi's free-form roof to compare New Method with the Kawaguchi method. The sample area had the highest amount of curvature on the Kawaguchi project's roof (except for the column area, where the box form method was adopted). The minimal radius was 1,179 mm, and the maximum Gaussian radius was 3.39e-07 (Fig. 4).

In this experiment, we made a free curved surface using four 900 mm × 900 mm units fabricated in the factory to compare the assembly times and costs of New Method and the Kawaguchi method.

4.2.2 Fabrication of test specimen

The test specimen was fabricated at a wood machining factory, which is good at compregnating and bending such sawn veneer. Each unit comprised two parts: one for the support system and another for the sheathing panel (Fig. 5).

Figure 5. New Method's formwork unit

Part 1. Support system

The supporting part was formed of a bottom plate and two sideboards. These were connected by two hinges at each end of the boards, meaning that the support unit could immediately be extended from a flat folded state. The adjacent units were rotated by 90° alternately and placed side by side. The tops of the sideboards were connected to an adjacent unit with screws at the edges.

Part 2. Sheathing panel

The sheathing panel was made of narrow boards (100 mm wide and 12 mm-thick) that were bent along a 300 mm grid of CNC-cut walls. The gap between each board was filled with a coating putty to ensure they were watertight. The sheathing panel was fixed onto the sideboards of the support system and screwed with a joint board.

The total cost of producing each unit was 20,000 JPY, and the working hours of each stage of the production process in the factory are shown below.

1. CNC-machine cutting: 0.5 man-hours
2. Assembling and setting the sheathing panel and the support: 6 man-hours

4.3 Analysis of workability and cost

In this section, we analyze the assembly process of New Method by dividing it into five sub-processes and measure each process's working time and compare the experimental results with the assembly time of the Kawaguchi project's on-site formwork.

4.3.1 Analysis of production time

The time taken to assemble the four formwork units was measured and analyzed in a factory's woodworking laboratory. Two unskilled workers conducted the construction experiment. All parts were folded at the beginning of the assembly process. At the end of the assembly process, all parts were assembled and joined in their designated positions. Table 3 shows the measured time for each sub-process.

According to the experimental results, New Method's assembly process takes 0.283 man-hours/m^2, which is approximately 12% of the working time of the Kawaguchi method's on-site process.

Table 3. Time for each assembly process in New Method

Process	Time (s)	Time per area(s/m2)
Transport and placement of support parts	410	126.5
Joinning of support parts	120	37.0
Transport and placement of sheeting panel parts	260	80.2
Joinning of sheeting panel parts	750	231.5
Others(preparation,transport)	110	34.0
Total	1650	509.3
Man-hour per square meter for total assembly process (man-hour/m2)		**0.283**

4.3.2 Analysis of shape accuracy

The 3D coordinates of the assembled formwork surface's shape were measured at a pitch of 100 mm using a 3D laser distance-measuring machine. We used a fixed-type surveying instrument that can calculate the 3D coordinates and angles of any point on the measurement object's surface through laser irradiation. The laser measures with an accuracy of ±1 mm at a distance of 10 m.

The distance error between each point on the specimen and the 3D model's surface was then measured, and the accuracy of the sample's shape was analyzed. Total Number of measurement points is 360.

Maximum negative error value: −7.4 mm
Maximum positive error value: +6.3 mm
Standard deviation of the population: 1.96 mm
Average of the absolute value of error: 1.86 mm

The surface error of New Method was much smaller than the construction error of the Kawaguchi method. The Architectural Institute of Japan recommends that such formwork's form accuracy error be maintained within ±20 mm [11] ; therefore, New Method has sufficient shape accuracy for this formwork's construction.

4.3.3 Cost analysis

The cost of constructing the formwork of New Method is detailed below.

1. Material cost: 24,600 JPY/m^2
2. Labor cost: 481 JPY/m^2 *1
3. Total direct cost: 25,081 JPY/m^2

*1: Non-professional labor cost:
1,700 JPY/man-hour[10]

The overall cost of formwork construction of New Method is higher by 31% than that of the Kawaguchi method.

5 Conclusion and discussion

In this study, we explained the conventional Japanese construction method of double-curved surface formwork. Based on examples of curved surface structures from the past 30 years, we classified and organized these methods by the structure and sheathing plate.

We then focused on a case study of a completed project with a 5,100 m^2 free-form RC roof built with conventional construction methods. We also analyzed these methods' time and cost of production based on the general contractor's construction records. The study results revealed that these methods depend heavily on on-site labor.

We then developed a new production method for reproducing curved surfaces with high shape accuracy without relying on existing advanced carpentry skills and field labor on-site works. We analyzed its productivity by performing assembly experiments. The proposed method reduced the project's on-site labor costs by 93% compared with those of the existing method.

In future studies, a more systematic and cost-optimized formwork program should be created by developing a cost- and time-efficient construction method that delivers a product with the accuracy required for the curvature of the area.

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