Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Verification of Flexible Cable-net Formwork Method for GFRC Panel Manufacturing Using Structural and Physical Optimization

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Abstract

The cable-net formwork method has attracted attention as a low-cost and environmentally friendly way to realise free-form concrete shells. In this method, the doubly-curved surface of the membrane is controlled through wire end position and tension; Block Research Group has clarified the design process[1], which has been used to realise large-scale prototypes[2][3].

On the other hand, few studies have examined items necessary for application to actual architectural production, such as accuracy and formwork reusability. In this study, cable-net formwork is applied to the manufacture of curved GFRC panels in Japan, and a highly flexible formwork method is proposed that allows the same formwork to be reused even if the panel outline, curved surface shape or curvature changes. Furthermore, a design method is also proposed to minimise errors between the target shape and the manufactured panel by using a method to calculate the initial tension and support conditions by structural and physical optimization.

Using the parameters determined by optimization, a total of 52 adjustable wire end positions is fixed. The tension of each wire is controlled by the number of revolutions of the turnbuckle, and different tensions are introduced for each wire as determined.

The above process produced four sets of two line-symmetrical panels, a total of eight panels, whose geometry was measured. Furthermore, the 3d-scanned panels were arranged onto the structural frame model and their position was also measured. Using these measurement data, the applicability of this method to architectural production was verified from three perspectives: reproducibility of target shape, reproducibility in manufacturing, and deviations in construction.

Keywords: form finding, optimization, concrete shells, cable-net structures, flexible formwork, shotcrete, GFRC manufacturing, doubly curved surface, 3d scanning

1. Introduction

In recent years, the demand for doubly curved RC elements has been increasing due to the spread of 3D modeling software and visual programming to designers. On the other hand, the current conventional curved RC construction and manufacturing method has the problem that it requires a huge cost for formwork manufacturing and a large amount of formwork waste after casting.

In the case of Japanese GFRC industry, the increase in the number of complex shapes is placing an increasing burden on factories, and the number of craftsmen is decreasing. To solve this problem, the Cable-net Formwork method has been attracting attention as a low-cost, environmentally friendly method of manufacturing curved RC panels.

In this study, the Cable-net Formwork method is applied to the Japanese GFRC shotcrete method, and the aim is to realize a curved surface GFRC construction method that does not impose a production load and generates as little waste as possible by making specifications that allow reuse even if the shape of each panel is changed. A design method that minimizes deviations by physical and structural optimization will be proposed, and the applicability of the method to actual architectural production will be verified by measuring the accuracy of the manufactured panels and positioning 3d-scanned panels onto the 3d model of the structural frame.

2. Related Works

A previous study using Cable-net Formwork for cementitious shell members was conducted, proposing a process for determining the formwork shape using physical and structural optimization (D. Veenendaal, and P. Block. [1]). Another study has realized a shell structure with Cable-net Formwork using knit fabrics and inflatable components (M. Popescu et al. [2]). A case study shows that a large scale shell structure is realized by a combination of Cable-net Formwork and cement shotcrete (P. Block et al. [3])

As described above, there are examples of large-scale mockups of cementitious shells realized with Cable-net Formwork. However, few studies have conducted the verification necessary for application to actual architectural production to realize mass customization, such as accuracy verification by comparing multiple panels from the viewpoints of both manufacturing and construction, use of flexible formwork considering reuse, and determination of formwork variables using optimization methods.

3. Design and Simulation

3-1. Outline of the Structure

To establish a highly flexible cable-net formwork manufacturing process and verify its effectiveness, the curved roof composed of eight GFRC panels, supported by an arched frame, is designed. These GFRC panels are designed to be attached to the wooden frame, serving as a curved roof shell structure that enhances the rigidity of the frame. The geometry of these panels is all designed with minimal curved surfaces. Minimal curved surfaces are known to have negative Gaussian curvature and can meet the requirements to be manufactured with Cable-net Formwork. The panels to be cast are A-1 to D-1 and A-2 to D-2, a total of 8 panels, and the panels with the same alphabet have a line symmetrical shape so that the deviations can be compared among symmetrical shapes to verify the reproducibility of the identical panels.

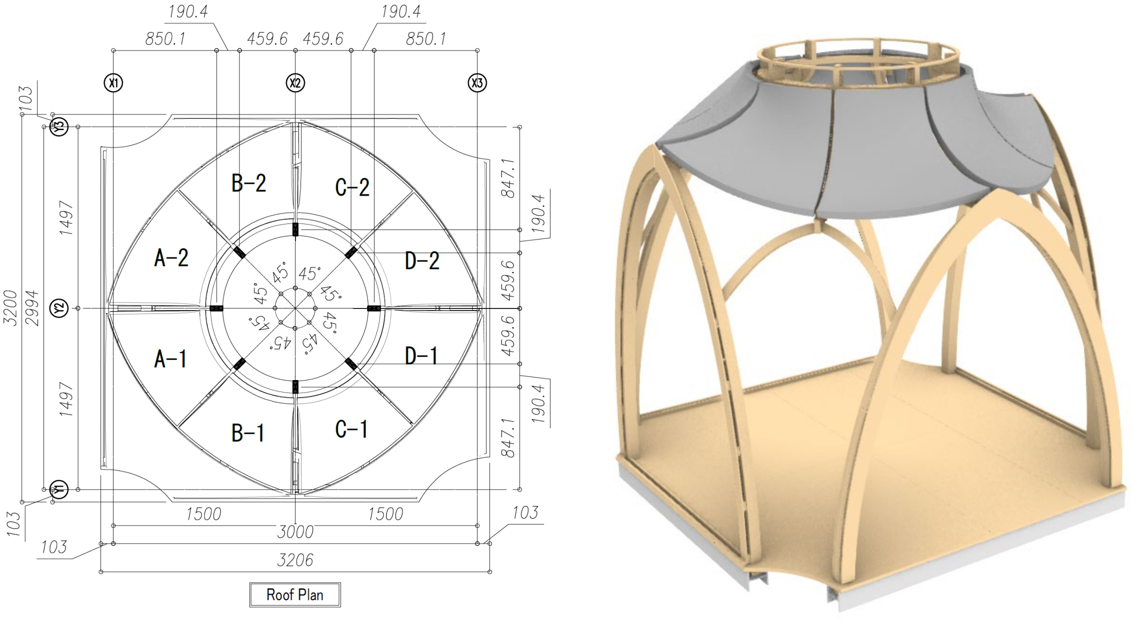


Figure 1: Composition of the GFRC panels

3-2. Panel Specifications

Panel backside view and cross-sectional view are shown in Figure 2. In order to achieve a balance between thin sheet thickness and structural strength, panels are accompanied by ribs, and inserts for joining with the frame need to be installed during panel manufacturing. The panel face thickness is 20 mm, and structural ribs of 60 mm wide and 30 mm high are placed around the perimeter. Inserts for panel mounting and cutouts for weight-bearing are provided at the four corners of the panel.

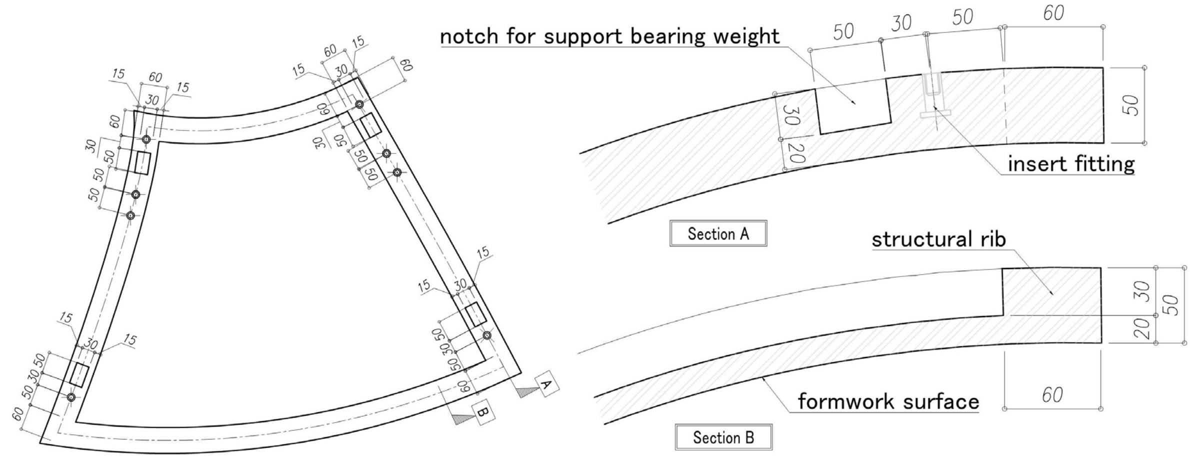


Figure 2: Panel Specifications

3-3. Formwork Design

The cable-net formwork used in this study is configured to control its shape with wires fixed by vertically movable steel support columns, with a membrane stretched over these wires to form the formwork surface. A steel formwork of size 1400 mm x 1400 mm was designed to support the wire and membrane. The height of each support column was adjustable within a range of ±250 mm so that the wire end position could be changed to match the curved surface shape of the panel. 13 support columns were placed at a pitch of 100 mm each, in a grid pattern. The wire pitch can be changed to 100 mm, 200 mm, 300 mm or 400 mm depending on the number of support columns used. In the production of GFRC panels in this study, all the support columns were used and the wire pitch was 100 mm.

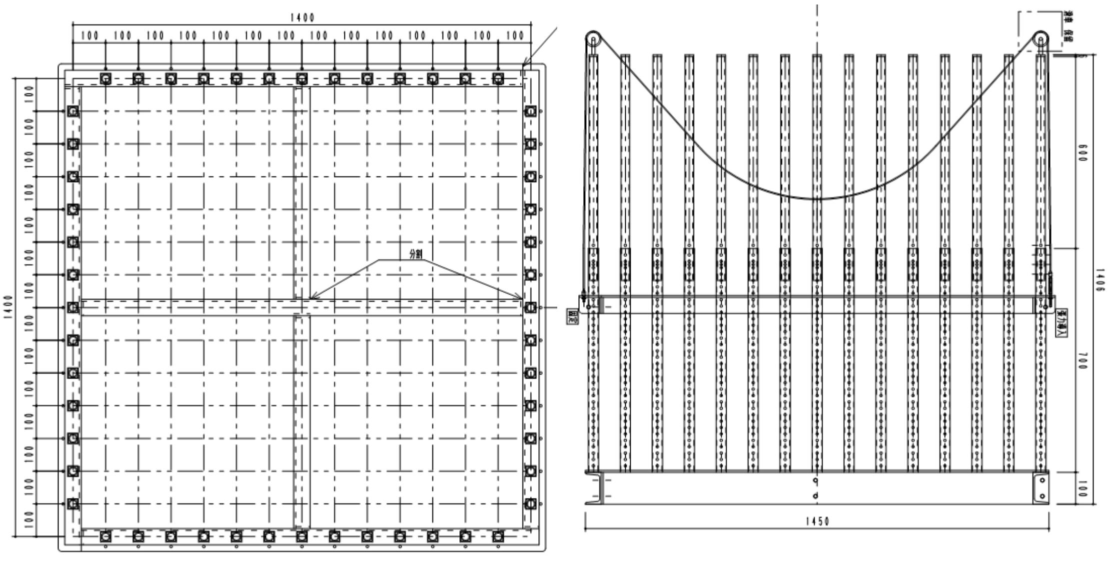


Figure 3: Steel formwork supporting membrane and wires

The membrane, which serves as the mold face, is made of stretchable polyester that can be stretched to follow the curved surface shape. To make bags for passing 3 mm diameter wires through the membrane, the membrane was layered in two layers and the 5 mm wide wire bags were sewn in a grid pattern with a sewing machine. Because the intersections of the grid intersected the vertical and horizontal wires, an 8 mm x 8 mm area was specified not to be sewn.

In previous studies, wires are joined at their intersections with metal hardware, and the membrane is attached to the wire grid created by the hardware (D. Veenendaal, and P. Block. [1], P. Block et al. [3]). With this method, it is necessary to adjust the positions of all wire-joining hardware each time the panel shape changes. With the method used in this study, once the wires are first passed through the membrane, the curved surface shape can be changed simply by changing the height of the end posts, making the cost of formwork adjustment very small.

On the other hand, in this method, it is challenging to control the positions of wire intersections and the lengths of wires between these intersections. Consequently, the curved surface is determined solely by the positions of the wire endpoints and the wire tension. As a result, it is considered that fine adjustments to the curvature of the surface become difficult.

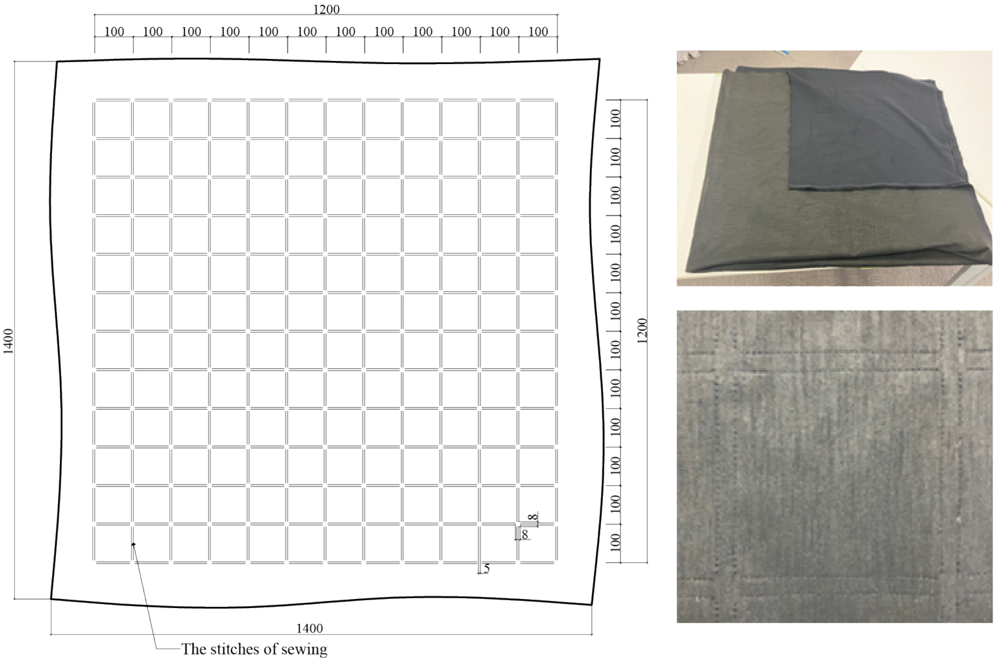


Figure 4: Membrane Specifications

3-4. Construction of Analytical Model

To predict the structural and physical behavior of the formwork shape with wire and membrane, the formwork was modeled using the Rhino+GH plug-ins Karamba and Kangaroo. First, the physical computing software Kangaroo was used to model the wire as a spring and to estimate the shape of the wire before it is subjected to the self-weight of the GFRC panel. The spring constant was estimated from measurements of the actually assembled cable-net shape. Changing the height of each wire end is input into the analytical model as a forced displacement in the Z-axis direction of the fulcrum, and the wire shape changes.

The resulting wire grid model is input to the structural analysis plug-in Karamba to create a beam model. The joints between the wires are to be rigid and the ends are to be pin supported. Each element is assigned a different initial tension for each wire. Among the points of contact on the beam model, the points of contact that are subjected to the self-weight of the GFRC panel are determined, and loads are input as nodal loads.

The above model construction allows us to estimate the shape of the wire and membrane deformed by the weight of the GFRC, considering the vertical adjustment of each wire end and the wire tension.

3-5. Design Process

As variables of the formwork, the position of the wire ends and the wire tension must be determined for each panel shape. The method for determining these variables is shown in Figure 5.

First, the wire end position and tension are tentatively determined according to the target curved surface shape. Based on the determined wire end positions and tensions, the shape of the wire and membrane is estimated using the Kangaroo physical calculation analysis software. The displacement of the estimated shape of the cable-net formwork under the weight of the GFRC panel is analyzed using the Karamba structural analysis software. The deviation between the shape obtained from the analysis and the target surface is calculated, and the position and tension of the wire ends are changed to reduce the deviation.

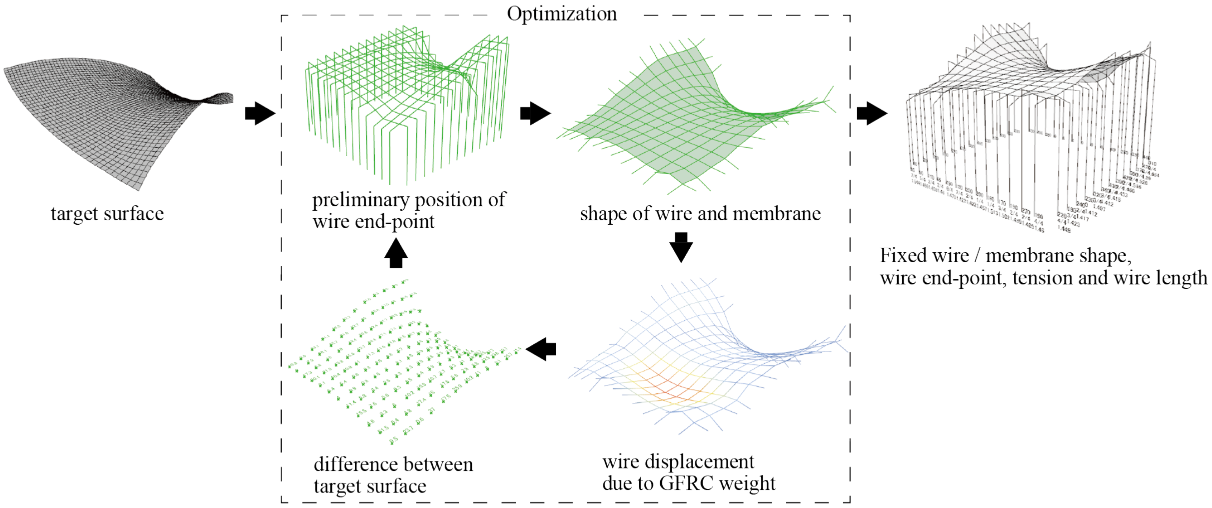
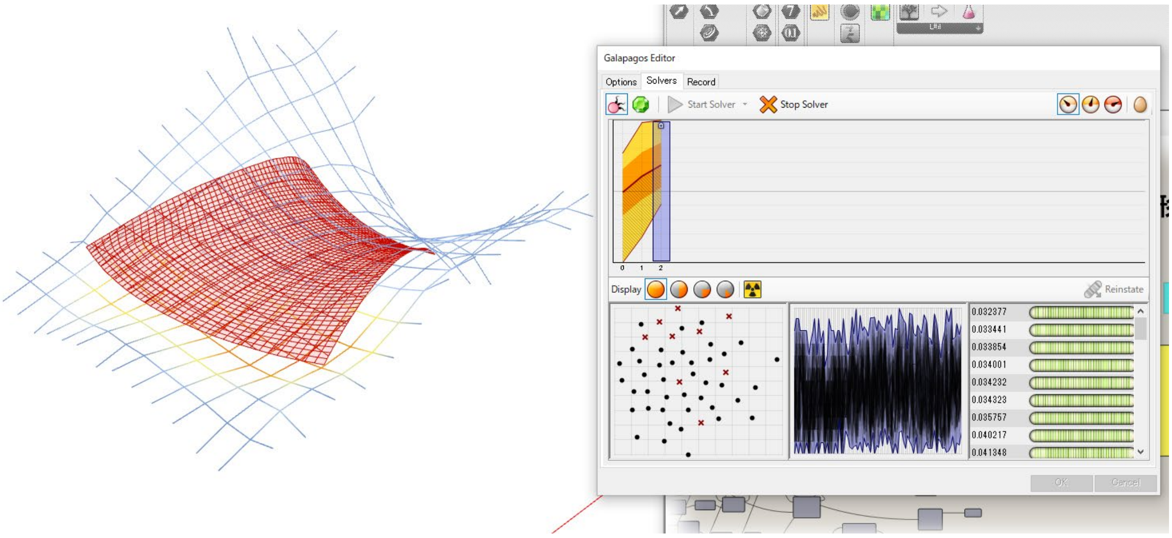


Figure 5: Process of determining formwork variables

A program to minimize the deviation between the formwork shape and the target curved surface shape by repeating this process was constructed using the genetic algorithm function of Rhino+GH. This program was used to determine the formwork variables (wire end height, wire tension, and wire length) for each of the eight panels (Figure 6). This design process, which included optimization using physical computation and structural analysis, allowed us to keep the deviation between the target geometry and the design formwork geometry to less than ±15 mm. Although this numerical value is sufficiently small as a tolerance for the panel surface, it exceeds the allowable tolerance for the coordinates of the joints. Therefore, in actual architectural production, it is necessary to focus more on minimizing the coordinate errors at the joints when setting the objective function for optimization.



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0.032377
0.033441
0.033854
0.034001
0.034232
0.034323
0.035757
0.040217
0.041348
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Figure 6: Optimization calculations including physical and structural simulations

4. Manufacturing of GFRC Panels

4-1. Adjustment and Tensioning of Formwork

In the manufacturing stage, we established a GFRC manufacturing process utilizing flexible cable-net formwork while adhering to conventional GFRC panel manufacturing processes and making modifications as necessary. First, a wire is fixed to the end of the steel formwork. The curved shape of the membrane is fixed by passing the wire through the bag of the membrane and introducing tension at the other end.

The wire tensioning method is The three methods of introducing wire tension are shown in Table 1. For panel A-1, tension was introduced starting from the wire at the end of the X direction toward the other end, followed by the wire in the Y direction in the same manner. For panels A-2, B-1, B-2 and C-1, the X-directional wire tension was introduced in order from the center wire to the end wires, followed by the Y-directional wire tension in the same manner. For panels C-2, D-1 and D-2, the X-directional wire was first loosened to the specified length determined from the simulation, and the Y-directional wire tension was introduced in the order from the center to the ends. The X-directional wires were then tensioned from the center to the bridge.

Table 1: Multiple wire tensioning methods for each wire

Panel No.	**Curved surface shape**	**Wire tensioning method (1-3)**
A-1	A	1. Introduce X-directional wire tension from the end, then Y-directional tension in the same way
A-2	A	2. Introduce wire tension in the X direction from the center to the ends, then introduce wire tension in the Y direction in the same way
B-1	B	
B-2	B	
C-1	C	
C-2	C	3. Loosen the wire in the X direction to the specified length and introduce tension in the Y direction in the order from the center to the end. Then introduce wire tension in the X direction from the center to the end in that order
D-1	D	
D-2	D	

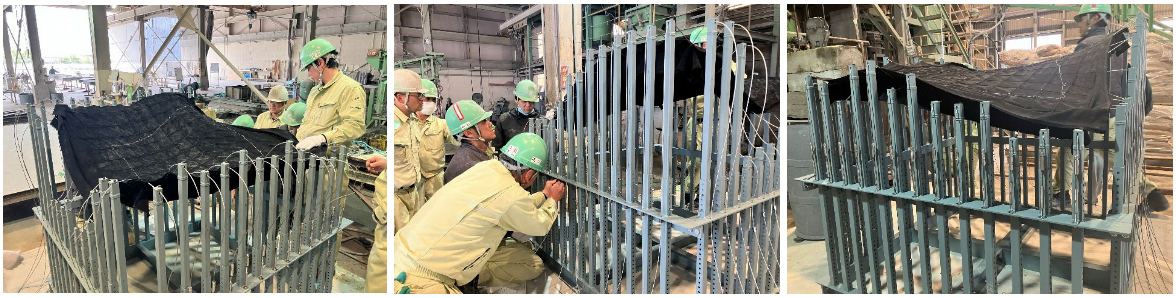

Figure 7: Adjustment and tensioning of the cable-net formwork

4-2. Casting and Compaction

After the adjustment of the formwork surface is completed, side frames molded by styrofoam are placed on the formwork surface fixed by wire tension. Then, GFRC is casted using a spray gun in the same manner as the conventional method. To prevent GFRC from dripping down due to the slope of the curved surface, the mortar flow value was set to 90 mm x 90mm.

In the conventional method, rolling pressure is applied using rollers and trowels, but in the case of Cable-net Formwork, the rigidity of the formwork surface is low, and pressure cannot be sufficiently absent. Therefore, a technique was adopted to increase panel strength by applying sufficient pressure to the GFRC by rolling with bare hands to release air.

Figure 8: Casting and Compaction of GFRC

4-3. Demolding and Finishing

After 24 hours of curing from casting, the panels were demolded. The polyester membrane could be easily demolded from the panel. The outer surface was finished with repeated localized convex surfaces due to the membrane being pushed up by the weight of the GFRC.

Figure 9: Appearance of the demolded GFRC panels

5. Verification of Accuracy

5-1. Manufacturing Accuracy of the Curved Surface

The weight of the cast panels and the accuracy of the cast surface were measured shown as Table 2. The weight ranged between 56kg and 67kg, which is approximately 1.1 to 1.3 times the intended weight of 50kg. This is considered to be caused by the fabric being compressed by the GRC weight, resulting in the formation of uneven surfaces.

Table 2: Manufacturing deviations of each panel

Specification				**Measurements**		
Panel No.	**Curved surface shape**	**Surface area [m2]**	**Wire tensioning method (1-3)**	**Weight [kg]**	**Maximum deviation [mm]**	**Mean deviation [mm]**
A-1	A	0.67	1. Introduce tension in order from the end	56	±80.4	±39.8
A-2	A	0.67	2. Introduce tension in order from the center	57	±62.8	±23.9
B-1	B	0.66		56	±49.6	±25.4
B-2	B	0.66		57	±37.2	±15.5
C-1	C	0.78		58	±58.6	±26.0
C-2	C	0.78	3. Loosen the wire in the X direction to the specified length and introduce tension in the Y direction	67	±41.6	±21.3
D-1	D	0.74		63	±52.6	±29.1
D-2	D	0.74		61	±54.6	±22.5

To verify the shape reproducibility, panels produced with the same curved surface shape and the same wire tensioning method were compared (B-1 and B-2, and D-1 and D-2). When comparing B-1 and B-2, considering there is a maximum difference of over 12mm, it is considered that the reproducibility of the shape is low. On the other hand, comparing D-1 and D-2, there is almost no difference in the maximum deviation and the average deviation is less than 7 mm, indicating that the change in wire tension introduction method has improved the shape reproducibility.

To see the difference in accuracy by wire tensioning method, we compared panels with the same curved surface shape but different tensioning methods (A-1 and A-2, and C-1 and C-2). The accuracy is considered to have been improved by the method of "2. Introducing tension in order from the center". Furthermore, comparing C-1 and C-2, both the maximum error and average error are smaller for C-2, suggesting that the method "3. Loosen the wire in the X direction to the specified length and introduce tension in the Y direction" can minimize the deviation the most.

5-2. Construction Accuracy of the Fastener Position

To verify construction deviations, it is necessary to verify the deviation of the fastener attachment positions of each manufactured panel from the intended mounting positions of the frame. The eight manufactured panels were 3D scanned with a laser scanner and placed on a 3D model to simulate the accuracy of the installation process. The scanned panel models were manually positioned so that all four joints could be properly fastened to the frame. An XYZ plane was set up for each fastener and the deviation for each axis was calculated.

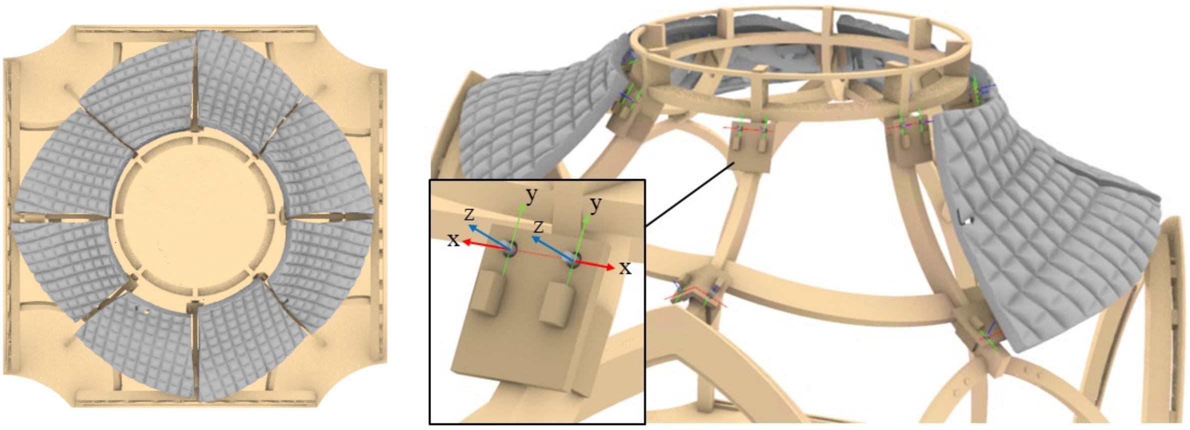

Figure 10: Arrangement of 3d-scanned panels (left), Deviation coordinate for each fastener (right)

In Table 3, the maximum and average values of the deviations of the four fastener positions on each panel are shown for each axis. When comparing the average deviations along each axis, it is evident that the deviations in the Y-axis and Z-axis directions are larger than those in the X-axis direction. The panel with the smallest deviation is B-2, as its average deviation is the smallest in all directions.

Differences in fastener position deviations due to wire tensioning methods are examined. When comparing A-1 and A-2, it can be observed that the deviation in the Y-coordinate is considerably larger for A-2 compared to A-1. Similarly, when comparing C-1 and C-2, the error in the X-coordinate increases for C-2 compared to C-1. Therefore, it can be inferred that the fastener positions are most accurate with wire insertion method 1, while method 3 exhibits the lowest accuracy.

It is revealed that the adjustment dimensions required for the manufactured panels are ±67mm in the X-direction, ±100mm in the Y-direction, and a clearance of +86mm in the Z-direction.

Table 3: Simulated construction erros of each panel

Panel No.	Wire tensioning method (1-3)	X coordinate deviation		Y coordinate deviation		Z coordinate deviation	
		Max. value [mm]	**Mean value [mm]**	**Max. value [mm]**	**Mean value [mm]**	**Max. value [mm]**	**Mean value [mm]**
A-1	1	-55.8	29.1	18.6	11.0	56.8	40.3
A-2	2	-32.4	27.1	75.6	46.0	63.9	42.8
B-1	2	-31.5	17.0	-66.8	26.0	80.0	49.7
B-2	2	41.2	16.6	20.5	11.9	20.8	14.6
C-1	2	39.3	18.6	52.3	38.8	85.5	50.6
C-2	3	66.4	22.7	48.3	33.4	71.8	52.3
D-1	3	52.3	26.3	96.4	49.2	68.9	42.1
D-2	3	24.7	17.2	-99.0	46.7	72.1	52.0

6. Discussions

We have calculated anticipated errors from both manufacturing and construction perspectives, revealing that these exceed tolerances acceptable in real architectural production. To mitigate these errors, enhancements in analysis precision, optimization settings revision, and the implementation of a formwork fine-tuning process during manufacturing are necessary.

Regarding the analytical approach, wires were modeled as rigidly jointed beams without considering wire-to-wire contact, yet discrepancies from actual wire behavior were observed. Therefore, constructing a nonlinear model where wires interact, and out-of-plane separation is constrained by a membrane is believed to enhance analysis accuracy.

In terms of optimization settings, prioritizing designs that minimize errors at joints is crucial. Treating joint coordinates and panel coordinates as equivalent led to significant discrepancies between digital and actual mounting positions. For GFRC panels, minimizing error in design coordinates of joints becomes paramount. Therefore, it is considered necessary to weight the objective function during optimization, prioritizing the error with respect to the design coordinates of the joints, or to perform multi-objective optimization with errors from both the panels and the joints.

In manufacturing methods, an effective strategy could involve adjusting formwork based on optimized numerical values, followed by using 3D surveying to measure errors between intended and actual formwork shapes. Developing a program to calculate necessary adjustments for wire strut heights and tensions to minimize these errors would further reduce manufacturing discrepancies. Facilitating such formwork fine-tuning should effectively minimize production errors.

7. Conclusion

In this study, we proposed a highly flexible cable-net formwork method for GFRC panel production in which the height of the wire end and the wire tension could be changed from panel to panel, allowing the formwork to be reused even if the curved surface shape and the outline of the panel changes. By using a method in which wires are threaded through a wire bag attached to the membrane, instead of the conventional method of joining wires using wire hardware, the cost of formwork adjustment was reduced to a minimum.

Furthermore, a design method was put into practice to minimize the deviation between the target curved surface and the actual formwork surface through optimization calculations using physical calculation and structural simulation software.

Eight panels were cast using this design method, and their manufacturing and construction deviations were measured. By comparing panels with symmetrical shapes, the reproducibility of the shape was verified, and by changing the method of wire tensioning in each panel, it was possible to clarify the differences in the deviations of curved surface shape and fastener positions depending on the tensioning method.

On the other hand, the accuracy verification from both manufacturing and construction aspects revealed that more accuracy is needed for application to actual architectural production. With further research, it is considered that accuracy improvements can be achieved through enhanced analysis precision, reassessment of optimization settings, and development of a formwork fine-tuning program.

In addition, the polyester material used as the facing material in this study had high elasticity but low rigidity, which resulted in the generation of locally convex and curved surfaces, and the weight of the GFRC was greater than expected. Possible solutions to reduce the weight of GFRC as a smoother surface include the use of a more rigid membrane material, pre-tensioning the membrane, and placing a thin layer of mortar on the membrane and placing GFRC after it has cured.

In summary, despite the increasing complexity of shapes in the GFRC industry in Japan, the continued use of conventional methods has led to serious labor shortages, factory fatigue, and the issue of formwork waste. By refining the methodology of the flexible cable-net formwork introduced in this study and advancing it to a level capable of meeting Japan's stringent accuracy standards, we hope to establish a method for manufacturing highly flexible shapes without imposing environmental or human burdens.

Acknowledgements

We would like to express our heartfelt gratitude to everyone at Nihon Funen Co., Ltd., Wakimachi Factory, for their invaluable assistance in manufacturing and measuring the GFRC panels used in this study. Their contribution was instrumental to the completion of our research, and we are sincerely thankful for their support.

References

[1] D. Veenendaal, and P. Block. "Design process for prototype concrete shells using a hybrid cable-net and fabric formwork," *Engineering structures*, vol. 75, pp. 39-50, 2014.

[2] M. Popescu, et al., "Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell," *Structures*, vol. 31, pp.1287-1299, 2021.

[3] P. Block, et al., "NEST HiLo: Investigating lightweight construction and adaptive energy systems," *Journal of Building Engineering*, vol. 12, pp.332-341, 2017.