MIN-MAX: REUSABLE 3D PRINTED FORMWORK FOR THIN-SHELL CONCRETE STRUCTURES

Reusable 3D printed formwork for thin-shell concrete structures

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Abstract. This paper presents an approach for reusable formwork for thin-shell, double-sided highly detailed surfaces based on binder jet 3D printing technology. Using binder jetting for reusable formwork outperforms the milled and 3D printed thermoplastic formwork in terms of speed and cost of fabrication, precision, and structural strength against deformation. The research further investigated the synergy of binder jetting sandstone formwork with glass-fiber reinforced concrete (GFRC) to fabricate lightweight, durable, and highly detailed facade elements.We could demonstrate the feasibility of this approach by fabricating a minimal surface structure assembled from 32 glass-fiber reinforced concrete elements, cast with 4 individual formwork elements, each of them reused 8 times. By showing that 3D printed (3DP) formwork cannot only be used once but also for small series production we increase the field of economic application of 3D printed formwork. The presented fabrication method of formwork based on additive manufacturing opens the door to more individualized, freeform architecture.

Keywords. Binder Jet 3D Printing; 3D Printed Formwork; Reusable Formwork; Minimal Surface; GFRC (GRC).

Aghaei Meibodi, M., Jipa, A., Giesecke, R., Shammas, D., Bernhard, M., Leschok, M., Graser, K. and Dillenburger, B.: 2018, Smart Slab, *ACADIA 2018*.

1. 1 Introduction

Glass Fiber Reinforced Concrete (GFRC) is an ultra-strong and flexible composite that contains a cementitious matrix composed of cement, polymers, glass and water (Corey 2010). In the last 30 years, GFRC has contributed significantly to the construction industry. It has been a great candidate for freeform thin shell facade and envelope cladding, due to its lightweight, high mechanical performance, durability, versatility, and aesthetics. Because GFRC is significantly lighter than concrete (about 75% lighter than traditional concrete with rebar), it's

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easier to handle on construction sites and install as cladding. That means the building envelope will be much lighter and consequently requires significantly less support structure (minimizing the structural load) thus helping to reduce the overall material use in buildings. GFRC is also considered a sustainable construction material as it uses less cement than equivalent concrete and often uses high quantities of recycled materials such as a pozzolan, recycled glass, metals, and other recycled materials. Its life cycle is longer than traditional concrete.

While almost many contemporary architectural buildings could be realised with an exterior GFRC envelope, the current inability to produce formworks with the intended geometry and successfully casting the GFRC elements with an acceptable surface quality is a prevention (Henriksen 2017). Thin and architecturally exposed cast elements such as free-form thin-walled GFRC cladding panels often require double-sided formwork. In order to cast the exterior surface and the connection details for mounting the panels to the building structure on the backside. For one of a kind elements or elements in small lot sizes, the cost for fabricating such formwork using traditional methods is a challenge. Besides the cost, the geometric freeform and surface resolution and detailing of a thin GFRC element would be very constrained when using traditional fabrication methods for formwork.

Additive manufacturing is a game-changer as it could enable the fabrication of freeform formwork with less cost, higher precision, and higher geometric freedom compared to the traditional methods of formwork manufacturing. Several additive manufacturing technologies are explored for fabricating formwork such as FDM (Peters 2014), wax (Gardiner 2016), thin shell FDM (Aghaei Meibodi et al. 2020), and FDM for dissolvable formwork (Leschok 2019 and Aghaei Meibodi et al. 2020). This research focuses on Binder Jet 3D Printing (BJP) as it offers the largest geometric flexibility, finest resolution, and highest precision among large scale 3D printing methods. In BJP with sand, a liquid binding agent is selectively dropped on thin layers of particle material to bind it. Industrial printers, originally developed for printing molds for metal casting, can fabricate molds at a very high resolution, in the range of a tenth of a millimeter, and at a maximum volume of 8m3 (Aghaei Meibodi et al 2019).

BJP formwork (BJPF) has already been used for concrete casting for example for a concrete truss (Morel 2014). BJPF was used for a thin shell sprayed concrete structure (Dillenburger 2016), and for a lightweight concrete slab (Aghaei Meibodi et al 2018). In those examples, BJPF was used as single-use formwork, which would need to be destroyed after its use. So far, the reusability of BJPF for concrete and its use for thin-shell double-sided formwork applications with GFRC has not been tested.

2. 2 Method

This research investigates the application of binder-jetting for fabricating reusable and double-sided concrete formwork that will be used to cast freeform GFRC elements. It investigates the geometric limitation that such formwork imposes on the cast part, as the demolding direction needs to be taken into consideration for the reusability of the molds. The performance of this fabrication method is compared to alternative fabrication methods (see Table 1). The investigation was carried through several small scale panels and a large scale demonstrator.

The first series of small-scale prototyping examined the potential of this approach for the production of high-resolution surfaces with geometrically complex detailing, surface finishing, and successful demolding of the cast part from the formwork. A series of panels with different geometric features that represent challenges for conventional milled molds were 3D printed. Those features are for example small concave features in the target part, which would require small convex features in the formwork. When fabricating such formwork with milling, this would lead to a long processing time and a large amount of material being subtracted (Figure 1 and 2). Successful demolding without chipping the cast or damaging the formwork was also a criterion that informed the design parameters for the detailing orientation of the parts. Another relevant parameter that informed the designed features and their orientation was the effective possibility to successfully demold the panels without chipping the cast or damaging the formwork

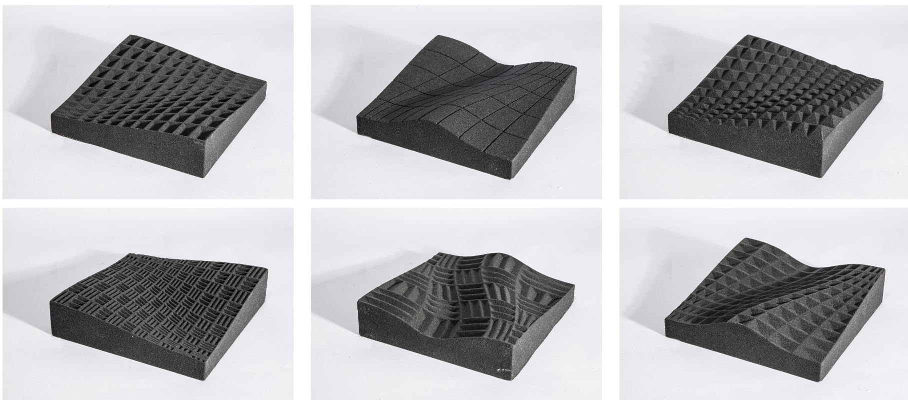

Figure 1. Series of 3d binderjet formwork tests with different surface characteristics (positive and negative features in different scale).

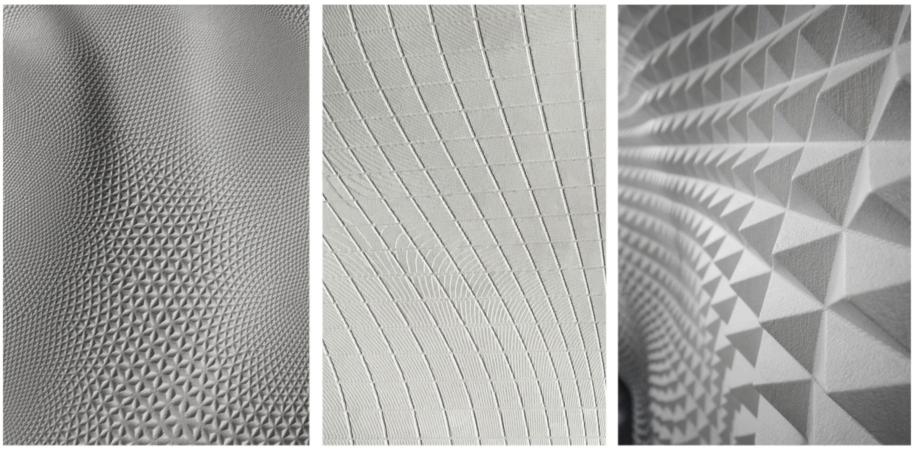

Figure 2. Resulting concrete casts of the first tests. Formwork could be removed non-destructively. The concrete shows all details down to the grains of the printed molds. In the middle sample, the structure of the 0.2mm high print layers is visible.

To evaluate the precision and accuracy of this method for large-scale GFRC freeform and thin envelope elements, we designed and fabricated a triply periodic minimal surface of the Schoen's "Batwing" family. Such a surface provides a valuable case study as it comprises sixteen equal quadrilateral parts, each of which sharing three edges with the neighboring ones and all meeting in one common point in the center of the assembly (Figure 3). This prototype was strategically designed in order to test the following criteria:

- ● Reusability
- ● Precision of interfaces
- ● Level of details of surface features
- ● Quality of freeform surface
- ● Fabrication time of the process

2.1. 2.1 FORM DESIGN

The design starts with Schoen's "Batwing" minimal surface. A minimal surface is a surface with a minimized total surface area for a given boundary. This surface can be adapted to several design possibilities. To describe the overall design, a computational method was developed to generate it as a NURBS. To obtain seamless adhering along the interfacing surfaces, an in-house bespoke function was developed that would take the designed surface as input and generate the thickness (Figure 3). The thickness was parametrically reformed for every feedback from physical prototyping to define the minimum thickness that can be successfully cast. A parametric subdivision method was developed on one side to showcase the level of details this formwork method allows.

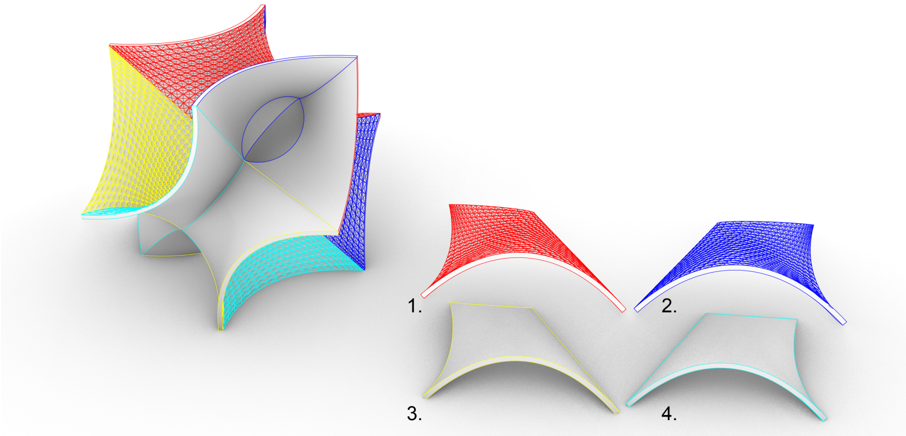

Figure 3. Segments of the concrete structure. The whole structure consists of one repetitive element and its mirrored copy; due to the ornamented details on one side of the surfaces, 4 different formworks had to be fabricated.

2.2. 2.2. FORMWORK DESIGN AND FABRICATION

The overall production required a total of four two-sided formworks, each composed of two elements assembled during the casting with the aid of a wooden frame: each part included bespoke connection details to ensure the precise relative positioning (Figure 4). To avoid potential occluded undercuts, we identified the optimal demolding direction using analysis tools provided by Solidworks which informed the design. Moreover, to overcome the brittle behavior of the 3D printed parts, each mold was infiltrated with epoxy resin.

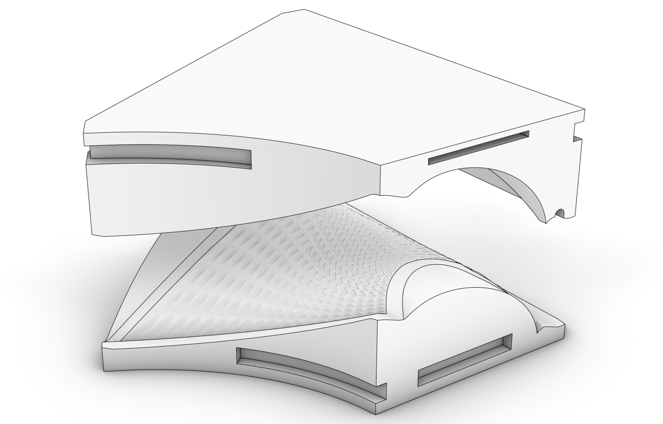

Figure 4. Schematic drawing of double-sided 3DP formwork with interlocking details.

The formworks were 3D printed using a commercial binderjet printer. The eight individual formwork parts were nested to fit in only one print box, allowing to minimize the overall costs of production and the printing time to only 16 hours. This is about 90 times faster than FDM 3d printing and 20 times faster than Milling (Table 1).

Table 1. Comparison of different manufacturing methods for a single formwork part (dimensions 760x685x170 mm, volume ca. 25 l). Postprocessing time is not included.

	Binderjet Printer	**FDM**	**Milling of MDF (3 Axis)**
Software	Materialise / Netfabb	Ideamaker (Simulation)	RhinoCAM (Simulation)
Machine	ExOne S-Max	Raise3D Pro	Generic 3Axis Mill
Material	Sand/Furan	PLA	MDF
Specific Process Parameters		10% infill (2 shell 0.4 mm)	Tool diameter: 12 mm Feed: 4000/6000 mm/min Speed: 6000 RPM Cut depth (roughing): 20 mm Cut depth (finishing): 2 mm
Layer height	0.3 mm	0.3 mm	
Processing-time	2 h	180 h	40 h
Weight Material	1 kg/l	0.21 kg/l	0.7 kg/l
Weight Final part	25 kg	5.2 kg	17.5 kg

2.3. 2.3 CASTING

A company focusing on prefabricated concrete facades performed the casting using a mix of GFRC specifically tailored to ensure the complete filling of the thin void of the formwork, measuring only 18mm. The material was cast through the single inlet positioned at the bottom of each mold to avoid air trapping. The porosity of the printed formwork allowed the excess air to flow out of the casted volume. The selected material is frost resistance, freeze-thaw resistance, UV-Resistance, and qualifies as a facade material (Table 2). The advantage of fabricating the panels with an indirect printing method, compared to direct printing, is that the excellent properties of the cast material can be achieved. The below specifications of the selected cast material outperform current properties which can be achieved with 3D printing.

Table 2. Table 2. Selected characteristics of the cast GFRC concrete.

Property	Symbol	Unit	Characteristic	Norm
Density	ρ	kg/dm3	2.0	EN 1170-6
Compressive strength	f ck	N/mm2	60	EN 196-1
Limit of proportionality (LOP)	LOP	N/mm2	8	EN 1170-5
Flexural strength	MOR	N/mm2	10	EN 1170-5
Elongation	ε u	‰	1	EN 1170-5
Elasticity	E	kN/mm2	30	EN 1170-5
Water Vapor Diffusion	μ		> 50	DIN 4108-4
Waterproofing	c ws	m2 h	< 10	EN 772-11
Thermal Conductivity		W/mK	0.8	EN 12664
Coefficient of thermal expansion	αT		10 x 10-6	DIN 51045

2.4. 2.4. ASSEMBLY

Due to the high precision rendering of the geometry enabled by BJP, the assembly of the single casted parts was performed with the auxilium of simple wooden frames. The parts were glued together by applying a two-component epoxy glue along the interfacing surfaces, and no significant post-processing was needed (Figure 5).

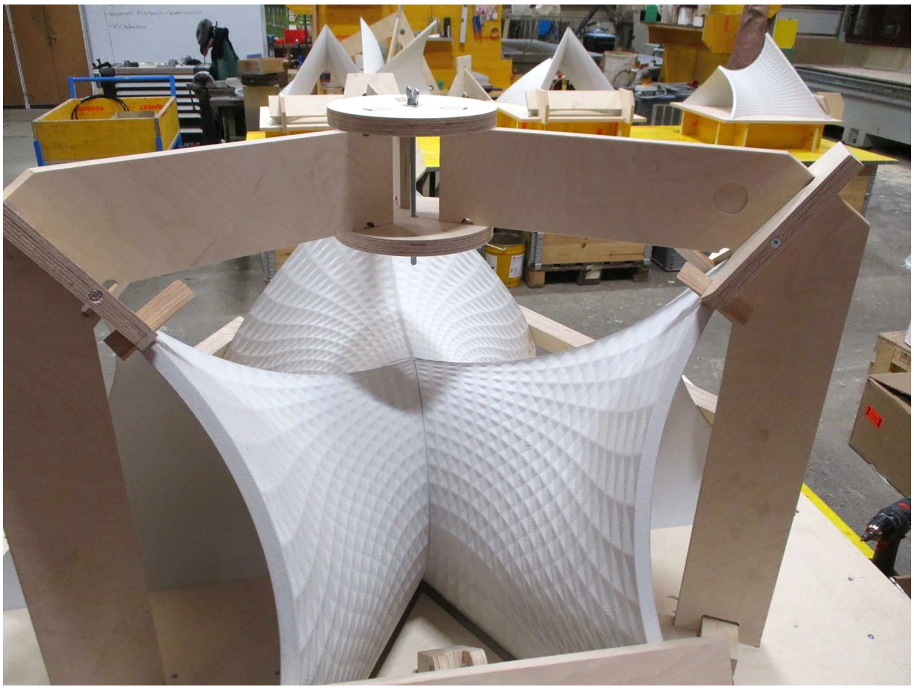

Figure 5. Assembly of the cast elements by gluing of the interfacing surface. The achieved precision of the edges plays a significant role in the construction of the entire structure.

3. 3 Results and Discussion

The result is a minimal surface structure assembled from 32 GFRC elements, cast with 4 individual formwork elements, each mold was reused 8 times. The accurate rendering of the cast elements allowed for the seamless assembly of the 32 parts with less than a millimeter precision at their interfacing surfaces (Figure 6).

Only minor post-processing steps were necessary. In comparison to 5-axis CNC milling with high-density foam, the manufacturing time can be reduced, and both the production of waste and the costs are considerably lower. The high precision of the printed parts resulted in cast components with remarkably smooth surfaces and sharp, sub-millimeter details (Figure 7 and 8), and allowed for the effortless assembly of the different elements.

The presented Minimal Surface Structure showcases a cast GFRC element based on binderjet formwork, where the freeform geometry, surface finishing, high resolution detailing, and high precision in assembly could be tested.

The surface quality achieved with this method is comparable to the results obtained in traditional concrete casting with milled formwork and silicon negatives. The intricate surface detailing could be fabricated with the same speed and cost of the smooth one, allowing us to rethink the role of detailing in architecture and its potential function as a passive means to control, i.e, the acoustic - or the energy-performance of the building envelope.

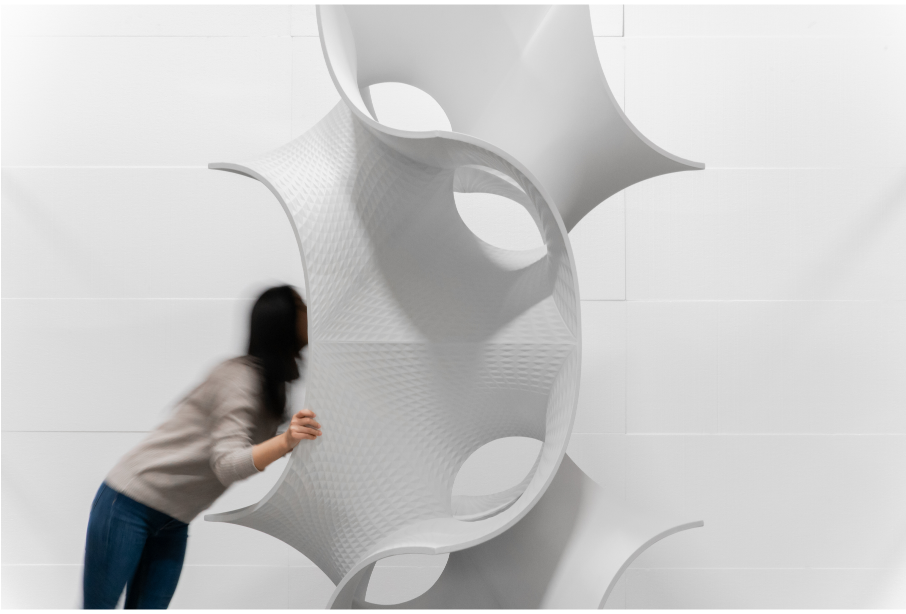

Figure 6. Min Max Structure as exhibited in Swissbau. An 18mm thin shell structure standing 2 meters high with minimal use of material (overall only 80 liters (40 per unit) of GFRC was used).

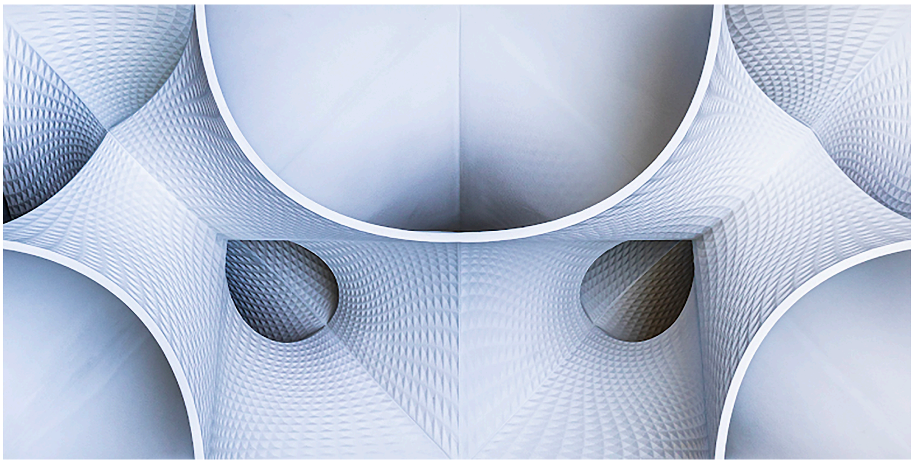

Figure 7. Min Max Structure close up details.

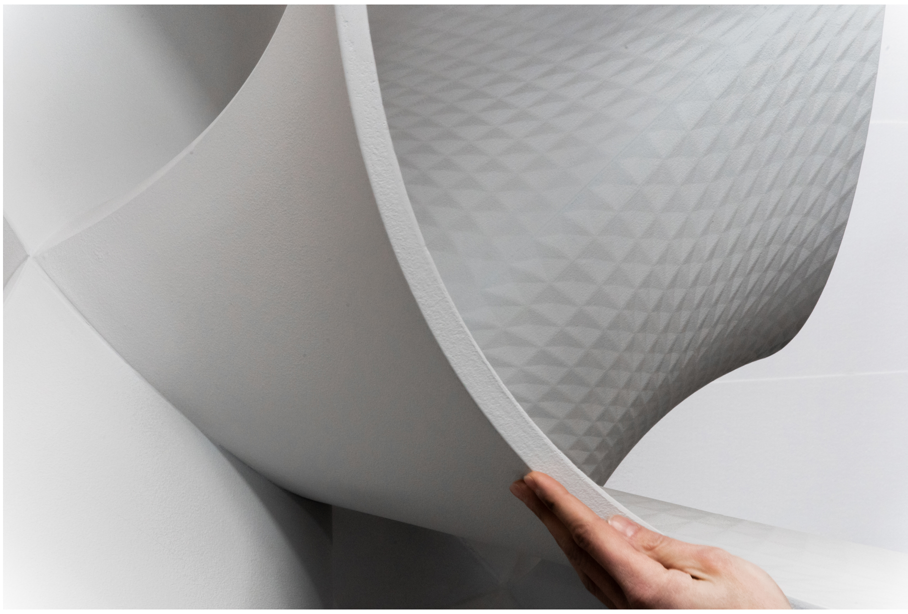

Figure 8. Close up of the surface showing fine surface details on one side and a smooth finish on the other side with an almost seamless connection of elements.

Finally, the use of 3d printed formwork renders the overall process considerably more efficient, minimizing the number of required production steps and decoupling surface detailing from production time.

4. Conclusion

The project demonstrates the production of repetitive parts from only a minimal amount of formwork. The two-sided, composite 3d printed formwork system in this project can be deployed for the production of any thin concrete element that requires high surface quality on all sides, such as free form facade elements.

The reusability of the printed formwork makes it attractive for small series of repetitive parts, which is often the case in architecture. However, in this case, the formwork parts need to be demoldable, which poses some geometric limitations on the GFRC elements.

The presented formwork method can contribute to lowering the entry-level for bespoke and freeform architecture. Hence, it could for example allow to individually adapt building facades better to a specific context, create spatially articulated facades with rich details, ultimately avoiding the monotony of standardized buildings. The presented double-sided form also allows creating lighter, thinner concrete elements, which can integrate details on both sides. It also expands the geometric freedom for building envelopes and enables more environmentally informed building envelopes.

The presented fabrication method of formwork based on additive manufacturing, opens the door to more individualized, freeform architecture using GFRC.combining this fabrication method with the minimal surface can enable the production of freeform lightweight facade elements with high-resolution surface detailing, which can be activated for a function such as saving energy or collecting CO2 emission in the air.

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