Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10 m high, self-supporting GFRC hyperbolic shell

Henriksen, Thomas; Lo, Stephen; Knaack, Ulrich; Kirkegaard, Poul H.

DOI
10.1080/17452007.2022.2096557

Publication date
2022

Document Version
Final published version

Published in
Architectural Engineering and Design Management

Architectural Engineering and Design Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/taem20

Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10 m high, self-supporting GFRC hyperbolic shell

Thomas Henriksen, Stephen Lo, Ulrich Knaack & Poul H. Kirkegaard

To cite this article: Thomas Henriksen, Stephen Lo, Ulrich Knaack & Poul H. Kirkegaard (2023) Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10 m high, self-supporting GFRC hyperbolic shell, Architectural Engineering and Design Management, 19:5, 480-510, DOI: 10.1080/17452007.2022.2096557

To link to this article: https://doi.org/10.1080/17452007.2022.2096557

Published online: 19 Aug 2022.

ARCHITECTURAL ENGINEERING AND DESIGN MANAGEMENT
2023, VOL. 19, NO. 5, 480–510
https://doi.org/10.1080/17452007.2022.2096557

Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10 m high, self-supporting GFRC hyperbolic shell

Thomas Henriksen [a], Stephen Lo [b], Ulrich Knaack [a] and Poul H. Kirkegaard [c]

[a]Faculty of Architecture, Department Architectural Engineering and Technology, Delft Technical University, Delft, The Netherlands; [b]Department of Architecture and Civil Engineering, University of Bath, Bath, UK; [c]Department of Engineering, Aarhus University, Aarhus, Denmark

ABSTRACT
The main bottleneck during the manufacture of complex geometry thin-walled GFRC structures is the time taken to make the timber or CNC machined moulds for each panel. Complex geometries are comprised of many unique panel forms and the extensive time and high costs of their manufacture often prevents their architectural intent from being fully realised. A novel mould-making process is proposed that uses a state-of-the-art flexible table with computer-controlled actuators to create free-formed geometry, fast-curing, dual-density, polyurethane moulds. This mould-making process was successfully tested by using sprayed GFRC to manufacture 9 different double curved intermediate moulds for a 10 m high GFRC self-supporting, thin-walled hyperbolic shell, with 12 mm thick panels at the base of the structure. The completed structure showcased the effectiveness of the novel mould-making process by reducing the production time from an estimated 100 days to 10 days. The primary outcome was the development and application of a new manufacturing method capable of casting complex geometry thin-walled GFRC panels with good surface quality that was suited to more rapid, cost-effective and automated large-scale production.

ARTICLE HISTORY
Received 16 July 2021
Accepted 27 June 2022

KEYWORDS
GFRC; complex geometry; moulds; sprayed method; flexible table; hyperbolic shell

Introduction to the challenges of manufacturing complex geometry thin-walled GFRC panels

Designing building envelopes with complex geometries using 3D CAD software has increased the demand for thin-walled glass fibre reinforced concrete (GFRC) (ACI 544.1R, 1996; ACI 549.2R, 2004; ACI 549.3R, 2009; Bentur & Mindess, 2007; Brameshuber, 2006; FIP State of art report, 1984; Fordyce & Wodehouce, 1983; MNL-128-01, 2001) for cladding landmark buildings and architectural infrastructure projects (Bekiroglu, 2010; Henriksen, Lo, & Knaack, 2015a, 2015b).

Complex geometries refer to true freeform building envelopes with little or no repetition of the panel form, requiring many, more costly, unique panels, as shown in Figure 4. Less complex geometries range from tessellated shapes that are reconfigured into a complex form (Figure 1), to geometries based on single curvatures (Figure 2), and double curvatures (Figure 3) (Henriksen, Lo, & Knaack, 2015b).

CONTACT Thomas Henriksen tnhenriksen@gmail.com Faculty of Architecture, Department Architectural Engineering and Technology, Delft Technical University, Delft, The Netherlands

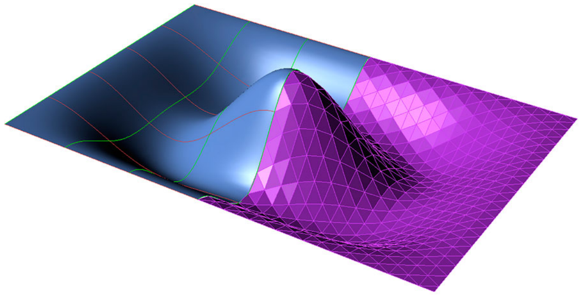

Figure 1. Tessellated freeform.

This research focuses on GFRC because it is able to deliver the surface finish and aesthetic uniformity required by complex geometry building envelopes. (Alternatives to GFRC such as steel-fibre reinforced concrete are mainly used in civil engineering projects where a smooth surface finish and no visible fibres are lower priorities).

The GFRC mix selected for this research was a widely used proprietary spray concrete mix (Andersen & Sørensen, 2016), using ordinary portland cement, but the precise proportions of the additives in particular are commercially confidential. The sprayed method was chosen as it allows the fibres to be added into the mix as it is sprayed to ensure that it is fully mixed on impact. The use of Ultra High Performance Concrete (UHPC) was disregarded because it is currently not possible to utilise UHPC with the spray method for complex geometry façade panels (Buitelaar, 2004). The viscosity of the concrete mix is too low to produce a uniform coat because it tends to slump on the more inclined surfaces of complex geometry surfaces.

The potential use of alternative more established 3-D formed manufacturing processes from other disciplines, such as wind turbine blades and aircraft wings, could also not be applied to complex geometry GFRC building envelopes, for two key reasons:

(1) Complex geometry wind turbine blades and aircraft wings utilise carbon-fibre reinforced plastic (GFRP) as the casting material.
(2) The casting of wind turbine blades and aircraft wings has high repetition of fewer specialist and costly moulds. This is not the case for complex geometry thin-walled GFRC building envelopes that require a higher number of unique moulds for many different individual panels. The high cost of so many unique moulds means that such projects are often not realised, or the building

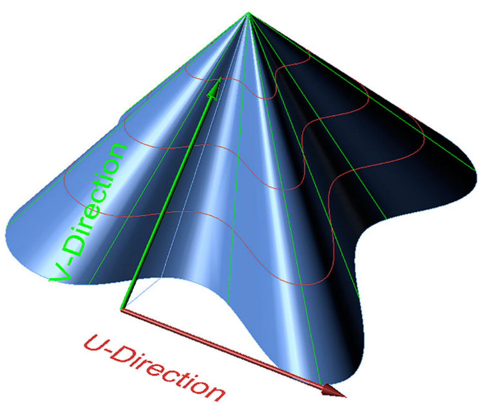

Figure 2. Single curvature.

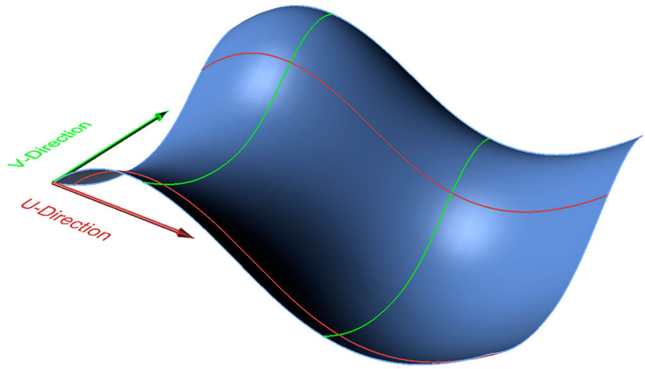

Figure 3. Double curvature.

envelope is simplified into a less complex form, or a more economic material than GFRC is selected (Henriksen, Lo, & Knaack, 2016a, 2016b).

State-of-the-art moulds used for the manufacture of complex geometry thin-walled GFRC panels range from timber moulds to 3D CNC machined steel moulds (Henriksen et al., 2015a). The restrictions of such moulds were evaluated against the three main production methods for thin-walled GFRC panels, the automated premixed method, the premixed method and the sprayed method (Henriksen et al., 2015b). This revealed that any proposed advances in the manufacture of complex geometry thin-walled GFRC must meet the key challenges of today's architectural demands, namely:

(1) Develop a manufacturing method that can fabricate complex geometry GFRC panels without the high costs and extensive time associated with using existing state-of-the-art GFRC moulds.
(2) Do so while delivering good surface quality, i.e. a smooth surface finish, with no visual fibres in the surface, minimal air-bubbles or voids, consistent colour across all thin-walled GRFC elements and no visible cracks.
(3) Produce a monolithic appearance by allowing an edge-return to each panel, making it appear thicker than it really is while still using a thin-walled construction to minimise overall use of materials.

Any advances require a rigorously tested, cost effective, less time-consuming method of producing many unique GFRC panels (Henriksen, Lo, & Knaack, 2016b). This paper seeks to achieve this by evaluating the potential limits of a proposed novel manufacturing method for complex geometry

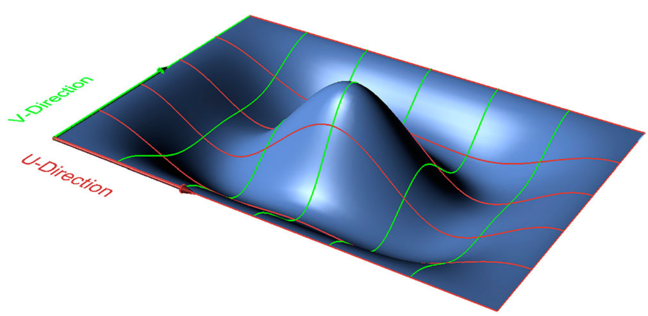

Figure 4. Freeform.

thin-walled GFRC, and realising a full-scale, 10 m, self-supporting complex geometry thin-walled GFRC hyperbolic shell.

Review of novel manufacturing process for complex geometry thin-walled GFRC

A novel manufacturing method for complex geometry thin-walled GFRC was developed as part of a research project to advance thin-walled GFRC for complex geometry applications (Henriksen et al., 2015a, 2015b, 2016a, 2016b). This method sought to resolve the aforementioned challenges from section 1.1 by:

- Making the fabrication of complex geometry thin-walled GFRC panels more cost effective.
- Reducing the manufacturing time of complex geometry thin-walled GFRC panels.
- Delivering thin-walled GFRC panels of good surface quality with edge-returns for a monolithic appearance.
- Allowing thin-walled GFRC panels of more complex geometries to be produced compared to panels fabricated using existing manufacturing methods.
- Devising a fully digital manufacturing process, from initial architectural concept to installed panel.

Methodology to develop cost effective fabrication of complex geometry thin-walled GFRC panels

To develop and test this novel process it was necessary to identify and resolve the main challenges during the manufacture of the moulds when producing complex geometry thin-walled GFRC panels. These challenges and their associated solutions are shown in Figure 5. This involved casting of GFRC panels in different moulds using 3 selected manufacturing methods that were evaluated for their suitability to meet the demands of good surface quality and edge-returns. Figure 5 also shows the key phases of the experimental procedure to find a more cost effective and rapid production method. Initially the suitability of a flexible table was assessed but was better suited as a 'mould-maker' than a mould. This was the starting point of the experimental procedure with each phase undertaken at test laboratories that specialised in each concrete application method.

The experimental procedure evolved as the findings and challenges from phase I informed the experimental procedure for phase II, that in turn, formed the basis of the methodology for phase III.

Background to phase I

Manufacturing complex geometry concrete panels has, historically, required timber formwork used for continuous concrete shells such as modern building envelopes designed by Torroja (2011, September), Candela (Alanis, 2008), Nervi (Lori, 2009) and Heinz Isler (Chilton, 2000) (Isler, 1960). This required in-situ casting using formwork that was time consuming to construct, difficult to add the reinforcement in-situ, and cast the concrete. With the development of computer numerically controlled (CNC) milling machines, it was possible to machine double curved geometries from materials other than timber so as polystyrene. Such processes are still time consuming and there is significant wasted material. A detailed description of the current development of formwork and moulds for complex geometry thin-walled GFRC are described by (Henriksen et al., 2015b). The development of flexible tables (Raun, 2011; Vollers & Rietbergen, 2007), adaptable formwork has enabled a more reusable technology. A flexible table has a single reconfigurable mould surface, with computer-controlled actuators capable of generating free-formed geometries. The state of the art in the use of flexible tables for complex geometry concrete was developed at TU Delft (Schripper, 2010, 2014) and Aalborg University (Raun, 2011, October 12). A flexible table was combined with an automated

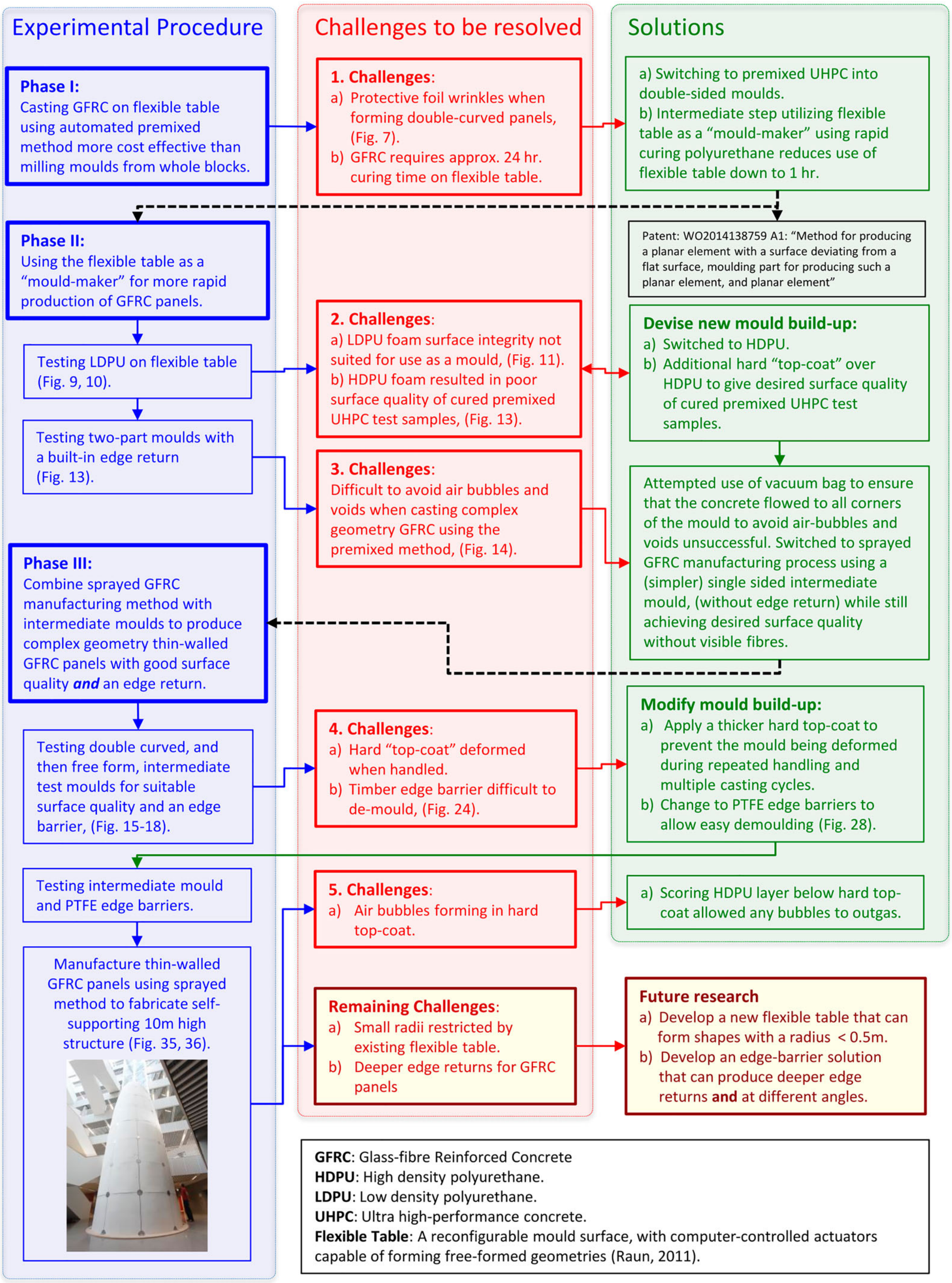

Figure 5. Key challenges and resulting solutions that emerged from 3-phase experimental test procedure.

premixed GFRC panel production line, Figure 6, to eliminate the need to produce the high number of individual, time-consuming moulds required by complex geometry forms. The premixed GFRC concrete panels were transferred from this production line while in their 'greenstate' to the flexible table to cure into their final geometric form.

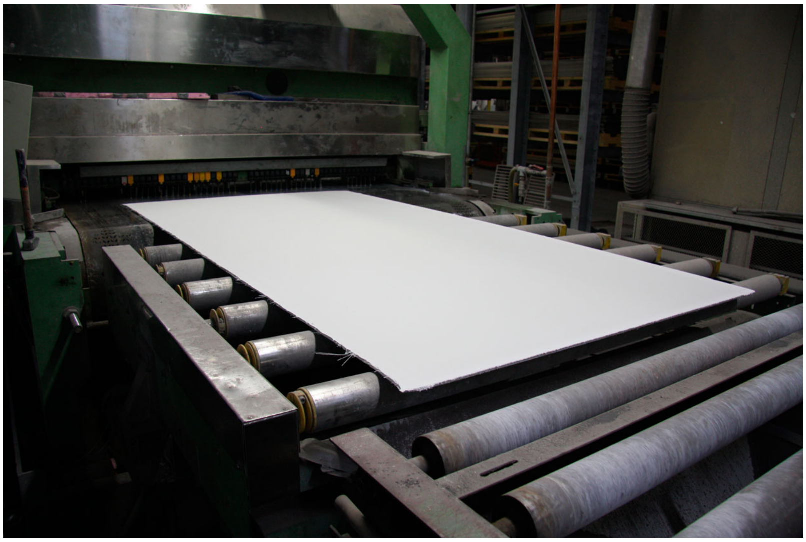

Figure 6. Automated production process for flat thin-walled GFRC (shown panel size ca 4 × 1.2 m).

The first issue arose from the protective foils used to ensure a good surface quality and protect the surface of the automated premixed concrete panels. The specification of the foils used were commercially confidential and when the flexible table was actuated to form a simple single curved form the foils remained intact, preserving the integrity and quality of the surface of the GFRC. Unfortunately, if double curved surfaces were attempted the foil would wrinkle and such imperfections were reflected in the surface of the concrete panels, visible in Figures 7 and 8 (**Challenge 1a,** Figure 5).

The second key issue was the necessary 24-hour curing time of the GFRC panel on the flexible table. Due to the high costs of flexible tables (£200 k – £1 m depending on size and number of actuators) fabricators rarely have more than a single flexible table, and as GFRC panels require up to 24 h to cure sufficiently to allow successful demoulding, each flexible table can only produce 1 GFRC panel per day.

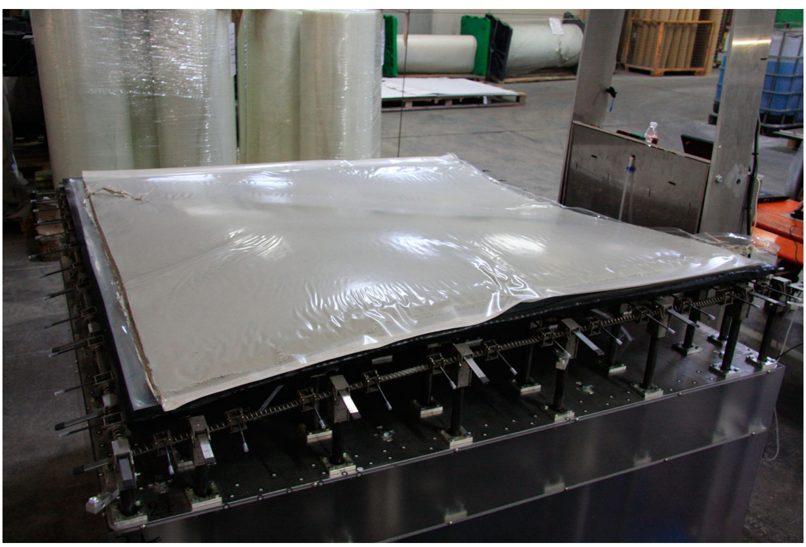

Figure 7. Automated premixed GFRC (panel 1,2 × 1,2 m), curing on a flexible table with the protective foil.

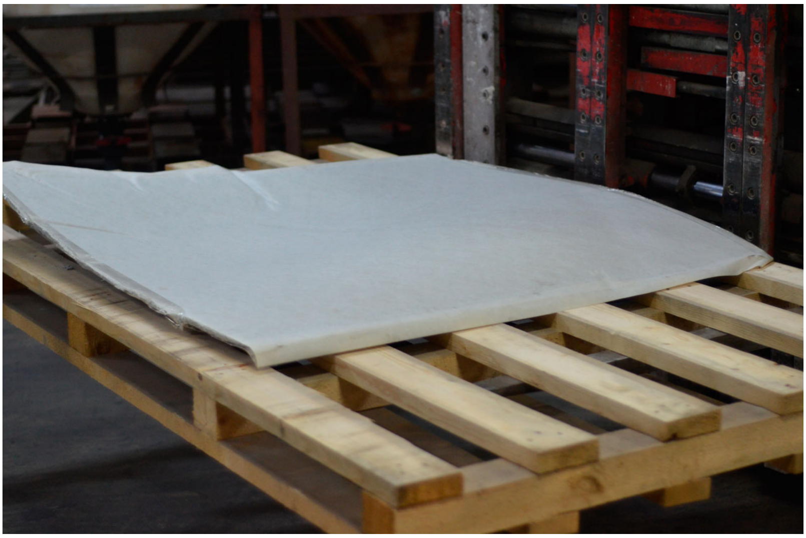

Figure 8. The automated premixed GFRC panel after curing and removal of protective foil. Panel 1,2 × 1,2 m.

For a single test sample, this 24-hour curing time was not a problem. However, such a lengthy curing period would hinder the demanding time schedules of projects today (**Challenge 1b,** Figure 5), creating a bottleneck in the production of large-scale building envelopes and could not be considered as part of a more automated and rapid manufacturing process for complex geometry thin-walled GFRC panels (Raun, 2011).

Phase II

This phase had to address the two key challenges that emerged from Phase I, namely, eliminating any damage to the GFRC panel from wrinkled protective foil, and to reduce the time that the flexible table was required for the forming and curing processes. The first challenge was addressed by replacing the automated premixed method with the (non-automated production line) premixed method, as the latter did not require protective foils. The second challenge was to improve the utilisation of the flexible table with a more rapid manufacturing process. The novel manufacturing process presented used the flexible table as a 'mould-maker' enabling intermediate moulds to be fabricated every 2 h. This in turn allowed at least 10 uniquely shaped GFRC panels to be cast each day, compared to just one per day when casting GFRC panels directly on the flexible table. Both positive and negative intermediate polyurethane moulds cured in 15–60 min (depending on the ratio of hardeners/foaming agent). Using the flexible table in this way as a 'mould maker' enabled the premixed concrete to cure on these separate low-cost moulds, rather than on the flexible table. This released the flexible table to make the next mould within an hour, and increased the GRFC panel output from the automated production.

The next step was to examine the viability of adding this intermediate step by assessing mould materials that were not only fast-curing but would be sufficiently robust to support the premixed GFRC panels. The performance criteria for suitable intermediate mould materials were identified below.

(1) Fast curing.
(2) Lightweight, with the capability to support the weight of the GFRC panels during the casting and curing process.
(3) Deliver continuously good surface quality.

(4) Good compatibility between the surface of the intermediate mould and the flexible table to ensure that the mould can be released undamaged.
(5) Good compatibility between the intermediate mould and the uncured GFRC to ensure that the surface quality of the mould is reflected in the GFRC panel.
(6) Durability of the intermediate mould for multiple casting cycles.

Different foam materials were evaluated against these requirements (Henriksen et al., 2016b) and the materials that met most of the performance criteria (polystyrene and polyurethane) were considered for preliminary testing. Initially, low density polyurethane (LDPU, 18 kg/m^3) foam was tried on the flexible table (Henriksen et al., 2015b), and the first prototype sample (40 × 40 cm) moulds of the resulting GFRC form are shown in Figures 9 and 10.

The LDPU allowed the intended geometric shape to be generated, and was capable of supporting the weight of the thin-walled GFRC while being cast, and throughout the curing process. Using oil-based releasing agents solved the compatibility issues between the foam and the flexible table. These releasing agents allowed the cured foam to be separated from the flexible table and again when the GFRC was cast onto the foam mould, both minimising mould damage, and extending re-usability of the mould. Unfortunately, the initial concrete casting test using this mould prototype showed that some of the surface of the LDPU had separated from the base material of the LDPU. The effects of this detached foam became visible on the surface of the concrete, as shown in Figures 11 and 12 (**Challenge 2,** Figure 5).

To resolve the problems of such a non-durable LDPU foam surface, a high-density polyurethane foam (HDPU, 128 kg/m^3), was considered as an alternative. Initial tests using HDPU for the entire mould were not considered cost effective so a mould comprised of a 20 mm HDPU outer surface over a LDPU core material was considered for the remaining tests. The full properties of the foam materials used are shown in Table 1.

Premixed method, because it also enabled UHPC to be used, allowing its material advantages to deliver high tensile capacity concrete while minimising problems with visible cracks in the surface. The method was based on a two-part mould system with a positive and a negative mould element, where the concrete was poured into the mould through feeder holes. Table 2 summarises the advantages and disadvantages of such an intermediate mould using the premixed method.

Figure 9. First sample of intermediate mould made with LDPU (40 × 40 cm).

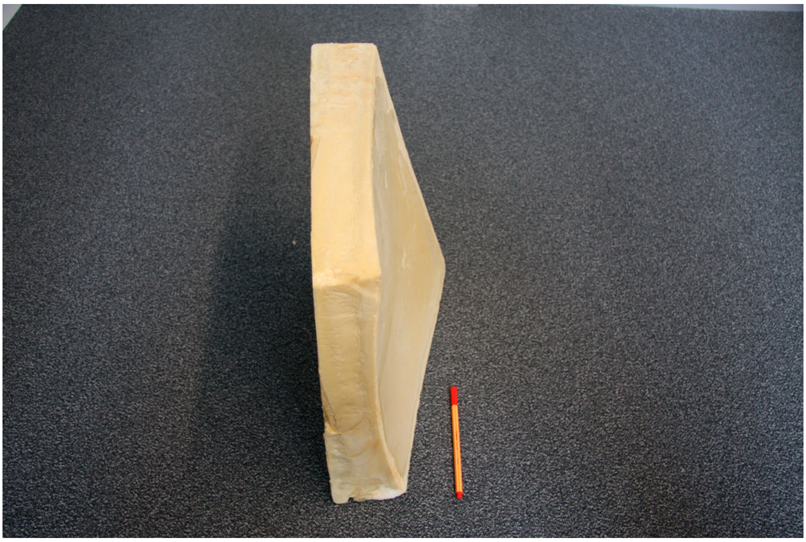

Figure 10. First sample of intermediate mould showing the double curvature of the mould (40 × 40 cm).

A small (23 × 23 cm) two-part intermediate sample mould, Figure 13, was tested for the premixed method.

The procedure showed that it was possible to successfully cast prototypes with a double curved geometry and an edge-return using the premixed method. This intermediate two-part mould for the premixed method was tested using ordinary Portland cement (OPC) without any aggregates and a viscosity that was low enough to allow it to flow to all parts of the 2-part intermediate mould. Test samples were made using moulds with an edge-return and the results of the tests are shown in Figure 14. The panel offset was not included as part of this initial test using the intermediate

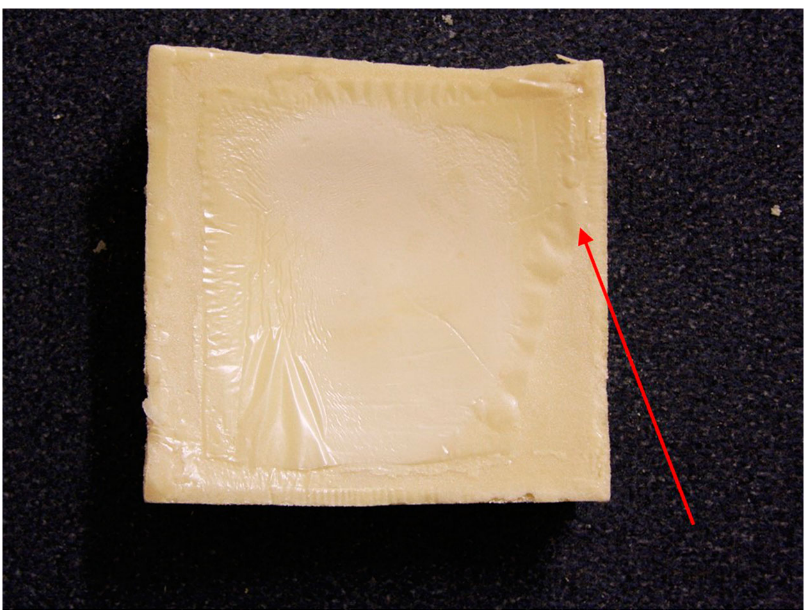

Figure 11. Intermediate mould with detached surface of LDPU foam, sample 23 × 23 cm.

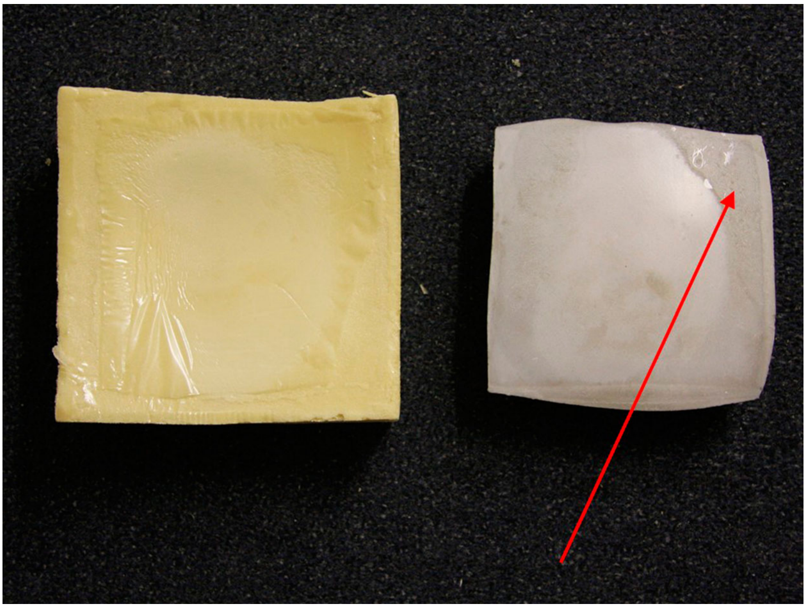

Figure 12. Premixed Concrete sample (18 × 18 cm) cast on the intermediate mould with marks from the detached surface of the LDPU foam (23 × 23 cm).

Table 1. Material properties for the foam material used in the 3 testing phases.

	Units	Hard Top Coat	HDPU	LDPU
Density	kg/m^3	1120	128	18
Volume	cm^3/kg	892	5202	–
Hardness	Shore	80	–	–
Ultimate tensile	MPa	26	–	0.18
Tensile modulus	MPa	903	–	–
Elongation at break	%	20%	–	–
Flexural strength	MPa	44	–	–
Flexural modulus	MPa	1413	–	–
compressive strength	MPa	34	–	0.05
Heat deflection Temp.	Celsius	55	–	–
Compressive modulus	MPa	328	–	–
Curing time	min	60	10	30

mould with the premixed method because it was difficult to avoid air bubbles and voids when casting complex geometry GFRC using the premixed method (**Challenge 3,** Figure 5).

Although the test was successful, a large-scale test was not undertaken because of the difficulties of ensuring that the GFRC flowed into all parts of a larger complex geometry mould. The premixed method was deemed less suitable for complex geometry thin-walled GFRC panels compared to the sprayed method, because:

(1) It was more complicated to cast complex geometry thin-walled GFRC panels using the premixed method than using the sprayed method because of the 2-part mould system.
(2) It was difficult to control the fibre distribution because the fibre-to-concrete ratio must remain low to allow the premixed concrete to be sufficiently viscous to flow to all the parts of the mould without voids and air-bubbles being created (Henriksen et al., 2015b). Avoiding such voids and bubbles became much more challenging when casting complex geometries, ultimately leading to rejection of the panels (**Challenge 3,** Figure 5).

Table 2. Advantages and disadvantages of forming an intermediate mould using the premixed method.

Intermediate mould premixed method	
Advantages	Disadvantages
UHPC can be used to cast GFRC using premixed method.	A two-part mould is required that doubles the cost and fabrication time compared to a single sided mould.
UHPC has a high tensile strength, allowing reduced thickness and longer spans between the support points.	To allow the concrete mix to easily flow into the mould and avoid clusters of fibres, premixed GFRC must have a low fibre to concrete ratio that reduces the bending strength. (The fibres are mixed into the concrete before it is poured)
An edge-return can be produced by making an offset when casting one half of the two-part mould.	A vacuum bag is necessary to avoid air-bubbles and voids in the cast surface of the premixed GFRC panel. This becomes more difficult with increasing panel size.
A panel offset can be made by making an offset when casting one half of the two-part mould.	The probability of visible air bubbles and voids is high for the premixed method and the rejection rate of premixed panels is higher compared to the sprayed method or the automated premixed method.
	Mould must be vibrated to avoid air-bubbles or voids,
	It is difficult to integrate any secondary support structure into a double-sided mould without having to destroy one of the mould parts when the cast GFRC panels are being demoulded.
	The use of UHPC for the premixed method is still under development for commercial use.

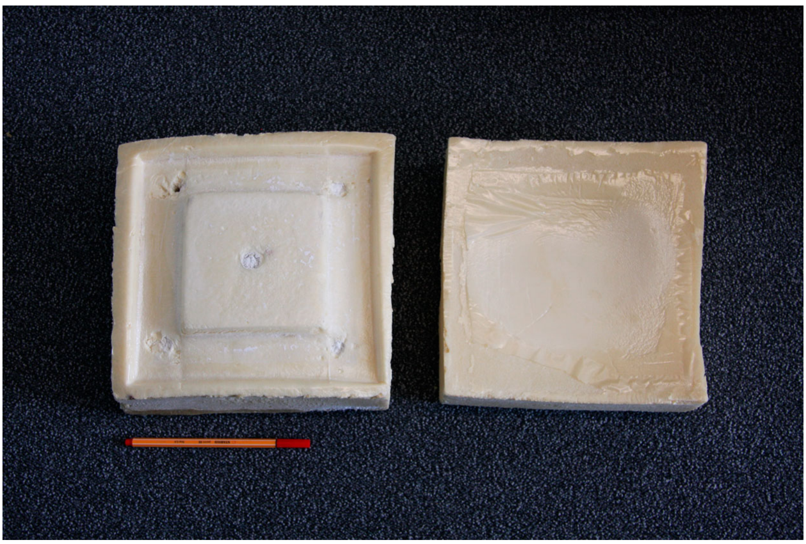

Figure 13. Small scale (23 × 23 cm) sample two-part intermediate mould for use with the premixed method.

Phase III

Phase III was designed to examine the suitability of the intermediate mould when using the sprayed method. Phase II highlighted challenges 2 and 3, namely poor surface durability of the intermediate mould and surface quality of panel after casting, key barriers to realising the full potential of this novel manufacturing method. Phase III developed a revised mould build-up to resolve these challenges and was tested at a manufacturing plant for sprayed thin-walled GFRC.

Phase II used double-sided intermediate moulds, however but would require a single sided intermediate mould to allow the sprayed method to be used. However, the drawbacks of single sided moulds in achieving the intended edge-return for complex geometric shaped GFRC panels compared to the mould devised for Phase II, remained. A solution was developed, but it could initially only produce edge-returns that were projected from the surface.

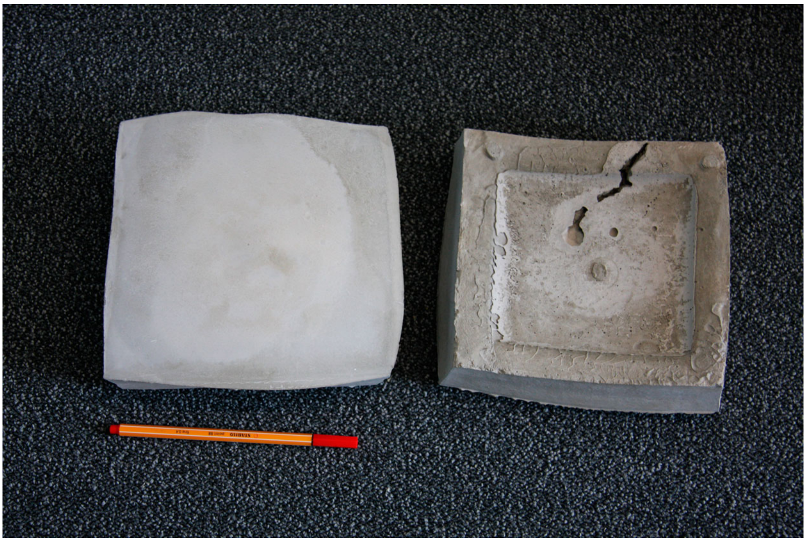

Figure 14. Premixed cast sample with small edge-return 18 × 18 cm. The samples show issues with the surface quality (Challenge 2) and air-voids (Challange3), i.e. key challenges that have to be mitigated.

The results of phase III would inform the manufacture of panels for a full-scale, 10 m high, thin-walled, GFRC self-supporting hyperbolic shell. The connection details for the thin-walled GFRC panels were tested in the laboratories at Aarhus University, where the shell was also erected. The new build up was comprised of:

(1) A thin top layer of sprayable polyurethane plastic (hard top coat).
(2) A support layer of HDPU foam to give rigidity to the hard top coat.
(3) A core of LDPU foam.
(4) A timber edge barrier.

The demand for sharp edge-returns and panel offsets generated from the intermediate moulds are key aspects required by today's complex geometry thin-walled GFRC architectural envelopes. Details of the terminology, and the demand for edge-returns and offsets in GFRC panels, are described in Henriksen et al. (2015b). It showed that the edge-return and the panel offset had to be integrated into the intermediate mould to allow complex geometry thin-walled GFRC panels with edge-returns and panels offsets to be cast.

Previous research suggested that the sprayed method was the most flexible way to produce such complex geometry thin-walled GFRC panels with an edge-return and a panel offset (Henriksen et al., 2015b). The outcome of the experimental procedure confirmed this to be the case.

A solution to utilise the flexible table to make an intermediate mould with the sprayed method was developed (Henriksen et al., 2016b). Developing the intermediate mould for the sprayed method using a flexible table with an edge-return was demanding because the negative mould would require an up-stand around its edge, so that an edge-return could be sprayed. Flexible tables with a continuous surface do not allow stepped edges in the surface, so an alternative approach had to be developed. The initial solution proposed an edge-return projected from the cast surface. The advantages and disadvantages of the intermediate mould for the sprayed method are shown in Table 3.

The first prototype to combine the new mould build-up developed from phase II, using a hard top-coat on the HDPU foam, all sprayed with a designated tool, is shown in Figures 15–18. The shape was a double curved geometry with the smallest radius being 1.5 m. Precise measurement of the panel dimensions and profiles was accomplished using (commercially classified) projected laser technology developed specifically for this application.

The hard coat consisted of an approximately 1 mm thick sprayed polyurethane plastic. This was used to ensure a good surface quality. The prototype was produced in approximately 4 h (disregarding the curing time).

A second prototype was made for a (more complex) free-form geometry (Henriksen et al., 2015b). The manufacturing stages for the second prototype are shown in Figures 19–22.

For the free-form shape a soft silicone edge was tested where there were high changes in curvature because a timber edge barrier would be too stiff to bend from a single straight piece of timber without cutting a bespoke shaped timber edge-barrier, as shown in Figure 22.

Following the production of these two prototypes the final sequence of the mould build-up was determined, namely:

(1) Project the shape on the flexible table.
(2) Outline the edges with a removable tape and foil.
(3) Apply the releasing agent.
(4) Spray the hard coat.
(5) Spray the HDPU foam and allow it to cure.
(6) Spray the LDPU foam.
(7) Attach the timber base.
(8) Attach the timber edge-barriers.
(9) Trim the unnecessary foam from the edge of the panel.

Testing the intermediate mould for the sprayed (GFRC) method

The first and second prototype intermediate moulds for the sprayed method were evaluated by an experienced fabricator of thin-walled GFRC (Brandt, 2015) and his findings revealed that the initial thickness of the hard coat allowed too much flexibility and could easily be deformed or damaged during handling or transportation. Any intermediate mould damaged at this point would leave marks on the cast surface of the thin-walled GFRC panel (**Challenge 4a,** Figure 5).

The prototypes for the sprayed method were tested with normal sprayed GFRC and compressed as described in (Henriksen et al., 2015a). Figure 23 shows the newly sprayed GFRC being compressed with rollers.

GFRC using the new intermediate mould, however, the edge barrier of the intermediate mould was made out of timber and was difficult to de-mould without damaging the thin-walled GFRC panel (**Challenge 4b,** Figure 5).

Table 3. Advantages and disadvantages of the intermediate mould for the sprayed method.

Intermediate mould sprayed method	
Advantages	Disadvantages
Single sided mould part can be used which reduces cost and fabrication time compared to the double-sided mould.	The current development only allows the edge-return has to be projected from the mould surface.
A face coat without fibres can be sprayed to avoid visible fibres in the surface of the panels.	The visual quality of the backside of the panel is not the same quality as the front side.
Secondary support structure can be integrated in panel to reduce the GFRC material.	The use of UHPC for the sprayed method is still under development for commercial use.
The fibre orientation of the GFRC can be controlled using the sprayed method.	
The thickness of the panel can easily be easily varied dependent on requirements and local reinforcements.	
Support anchors can be sprayed into the panel and reinforced locally.	
The panel can be reinforced locally, adding sprayed fibres perpendicular to the tension stress in the material.	

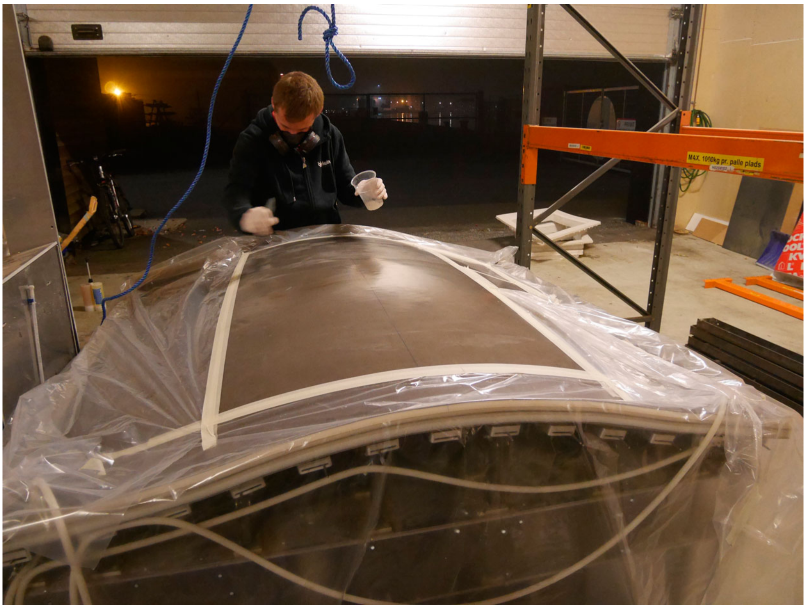

Figure 15. Setting out of the tested mould shape on the flexible table and adding the first layers, panels size 1 × 0.5 m.

Figure 24 shows the cured panel being released from the intermediate mould, but the single silicone edge-barrier that was applied on one side of the free-form mould did not detach from the cast concrete as it was pulled out of the mould. It was therefore decided in future tests to use polyethylene (PE) plastic based edge-barriers.

The quality of the free-form thin-walled GFRC panel met the requirements of a smooth finish over the whole surface with an edge-return of the same surface quality as the top surface, Figure 25.

Figure 16. Curing of the HDPU foam on the flexible table.

Figure 17. Curing the LDPU on the flexible table.

Figure 18. Fitting timber edges barriers on the mould.

Based on the experience from casting the thin-walled GFRC panels on the intermediate mould a hard top-coat layer of double the thickness was added to make it sufficiently durable to allow multiple casting cycles, handling and transportation of the mould. The timber edge barriers were changed to plastic to allow demoulding and to ensure a good surface quality of the edge-return, however, the plastic edge barriers were limited to larger radii (R<1 m) with a constant curvature and small edge-returns.

Figure 19. Setting out of the tested mould shape on the flexible table.

The third prototype intermediate mould to fabricate GFRC panels using the sprayed method followed the same steps as the second prototype. The timber support base, required to support the panel during final curing, was also simplified and reduced in weight as shown in Figure 26.

Figure 27 shows the demoulding of the new intermediate mould for the sprayed method with the edges of the mould replaced with plastic edge barriers to ease demoulding.

Figure 28 shows the new plastic edge barriers being fitted. In addition, the plastic barrier was made removable so that it was possible to remove one of the sides to ease the release of the sprayed GFRC panel when demoulding. This step also protected the mould and allowed it to be re-used more often compared to the first and second prototype.

The third prototype was successful, and the intermediate mould fulfilled the requirements for a continuous and good surface quality that could also endure transportation and handling as shown in Figure 29. The combination of the hard top-coat, the HDPU and the LDPU foam, reduced the cost of the mould (ca. 50% at 190 Euro/m^2, 2018 prices), compared to state-of-the-art CNC milled moulds. In Phase III a low-cost slow-curing hard top-coat was used, taking approximately 60 min before demoulding, however, if a faster curing hard top coat was used the curing time could be reduced to 15 min from first pour to demoulding. Adding the LDPU to a timber support base could be done at a separate work-station, releasing the flexible table to form new intermediate moulds of a different geometry. This would reduce the production time of the mould from days (for CNC machining), to hours (for the mould described above), depending on the complexity of the shape.

Material waste of the complex geometry intermediate mould for thin-walled GFRC was reduced compared to state-of-the-art CNC machined foam and timber (Henriksen et al., 2016a). The cost of single intermediate moulds when commercialised was projected to be approximately 250 Euro/m^2 (Henriksen et al., 2016a), half of the cost of state of the art CNC machined moulds. Any re-use would reduce the specific costs per m^2 of free-form GFRC still further, leading to an overall reduction in the total cost of free-form thin-walled GFRC envelopes. Ultimately, this will enable more complex geometry thin-walled GFRC building envelopes to be realised by improving their economic viability.

To test the feasibility of an edge-return a small 0.5 × 0.5 m sample was made to demonstrate an edge-return. The edge-barrier used for the small test was thicker (40 mm) than the 10 mm hard (Shore 80) silicone-based barrier used for prototype 3 as shown in Figure 30.

Figure 20. Applying the hard coat.

The intermediate mould with the 40 mm edge-barrier was successfully tested with the sprayed method, as shown in Figure 31; demonstrating that such a mould can be used to produce panels with an edge-return if they are projected from the surface.

The new intermediate mould using the sprayed method was the best option, since the premixed method had too many constraints, preventing it from being utilised fully compared to the sprayed method.

Assessing results of real-world viability by fabricating a thin-walled complex geometry GFRC self-supporting hyperbolic shell

The experimental procedure evaluated the viability of the novel manufacturing method for complex geometry thin-walled GFRC. Once validated, this method was used to fabricate a complex geometry thin-walled hyperbolic shell, comprised of double curved panels, as shown in Figures 32–34. This shell was developed in conjunction with the architect Ben Allen for a design competition (Ben Allen, 2014). The structure was based on a hyperbolic shape used by Antony Gaudi for the Church, La Sagrada Familia in Barcelona (Burry, 1993) (Castellar-Gassol, 1999), selected for being a perfect compression form when turned upside down. Unfortunately, the competition entry was unsuccessful so it was decided to build the hyperbolic shell as part of research collaboration between TU Delft, TU Darmstadt and Aarhus University.

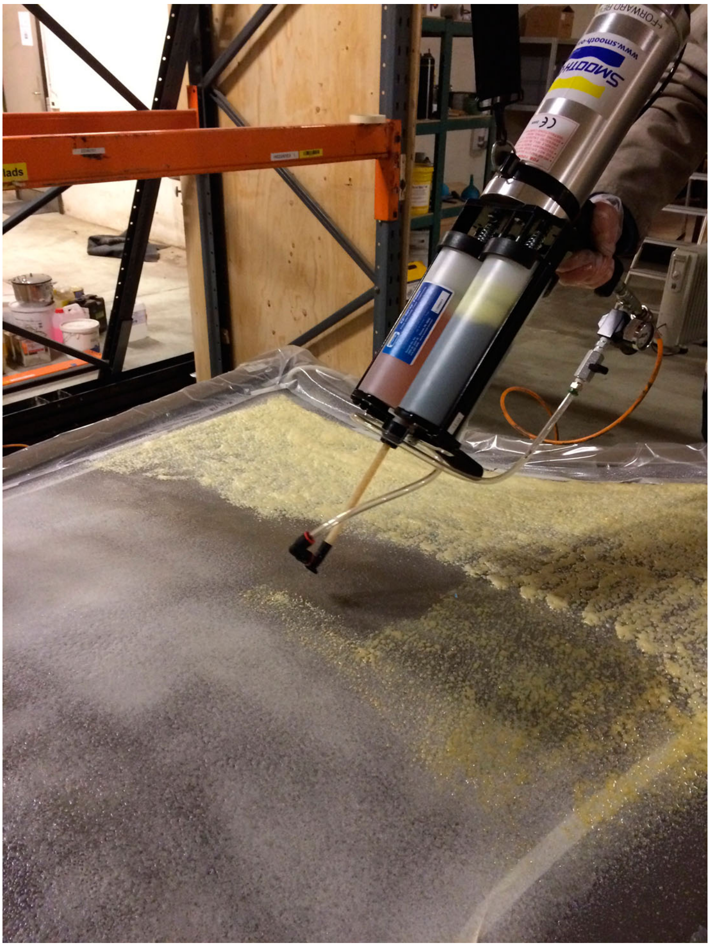

Figure 21. Applying the HDPU.

Figure 31 shows the principle of a catenary shape that when turned upside down, creates a perfect compression shell. Initially, a bespoke entrance was envisioned, as shown in Figure 32, but was removed as the design evolved to reduce the number of different panels. Figure 33 shows the final form of this hyperbolic shell, printed as a 1:500 scale 3D thermoplastic model before manufacture.

The hyperbolic shell (Chilton, 2000; Isler, 1960) was modelled using 3D parametric tools to generate the panel sizes and their geometry. The hyperbolic shell was comprised of 9 rings with 10 individual thin-walled GFRC panels and a top dome. The bottom ring of GFRC was comprised of approximately 1.2 × 1.2 m panels and mildly double curved with a radius of 1.5 m. The self-supporting hyperbolic shell was a discretised structure and the optimal wall thickness of the panels for each ring was calculated using 3D structural FEM software, with the structure dimensioned for indoor conditions allowing a wind load of approximately 0.45 kN/m^2 (Henriksen, Lo, & Knaack, 2015).

Analysing the connection details for the self-supporting GFRC hyperbolic shell

Before commencing the manufacture of the panels the hyperbolic shell was analysed for its structural behaviour and capacity. The result of the analyses showed that when using sprayed GFRC, a wall thickness of 12 mm for the panels in the bottom two rings with a limit of proportionality

Figure 22. Fitting edges on the mould.

Figure 23. The finished sprayed GFRC being compressed with rollers to mitigate voids and air-bubbles in the GFRC.

(LOP) (Ferreira & Branco, 2007) of 11 MPa, was sufficient, and a wall thickness of 10 mm was sufficient for the panels in the remaining rings of the hyperbolic shell. The connection details between the panels were sized as part of an FEM analysis, and showed that connection could be achieved successfully with standard M12 bolts (Andersen & Sørensen, 2016; Henriksen et al., 2015). To maintain the rigidity of the connection and buckling capacity of these thin-walled GFRC panels, a connection with a 10 mm thick GFRC panel was tested for its tensile capacity with two 2 mm stainless steel lash plates (since only the bottom two rings were made of 12 mm thick GFRC). The tensile test showed that the capacity of the 10 mm thick GFRC plates could accommodate an average of 7.0 kN in pure tension. The FEM model of this test arrangement showed a capacity of 6.4 kN. The design load for each bolt connection in the most critical connection was calculated to be 3 kN, so the connection capacity of the discretised thin-walled self-supporting GFRC hyperbolic shell was utilised by less than 50% (Andersen & Sørensen, 2016; Henriksen et al., 2015).

Figure 24. Demoulding of the free-form prototype.

Figure 25. The finished free-form GFRC panel after demoulding.

Fabrication of intermediate moulds for thin-walled complex geometry GFRC panels

To manufacture the thin-walled GFRC panels, 9 different intermediate moulds were produced for each ring of the hyperbolic shell, Figures 35 and 36, with 10 identical panels in each ring. This allowed each intermediate mould to be reused 10 times. The intermediate moulds were produced using the method shown previously in Figures 26–29.

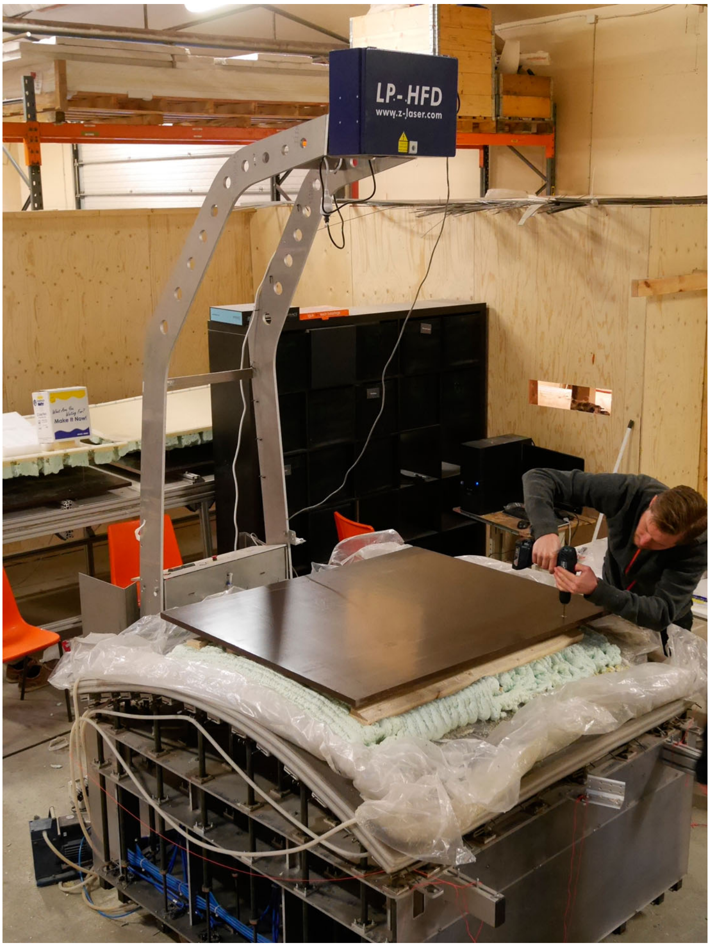

Figure 26. The simplified timber base plate being fitted to the foam part of the intermediate mould.

However, the changes to the edge material and the hard top-coat resulted in some unexpected side effects, namely, bubbles created in the surface of the hard top coat, visible in the completed GFRC panels (**Challenge 5a,** Figure 5). But the surface quality of the cast surface of the GFRC against the CNC machined mould did not meet the aesthetic demands and the CNC machined mould could easily be demoulded. The air bubbles formed in the hard top-coat could be avoided by resolving the compatibility between the different materials used in the intermediate mould. However, due to laboratory time constraints it was not possible to create new moulds for the production. An intermediate mould for the top of the hyperbolic shell could not be made with the current flexible table because the radius of the top piece was too small so a conventional mould had to be milled using a CNC machine (Challenge 5b, Figure 5). This challenge could, in future, be met by using a smaller flexible table with more actuators and more closely spaced pistons.

Manufacture of thin-walled complex geometry GFRC self-supporting hyperbolic shell

The installation of the thin-walled GFRC self-supporting hyperbolic shell was undertaken at Aarhus University, Faculty of Engineering. The bottom of the structure consisted of a timber floor plate that acted as an ultimate stiff plate. A small grove was milled in this timber floor plate to enable the

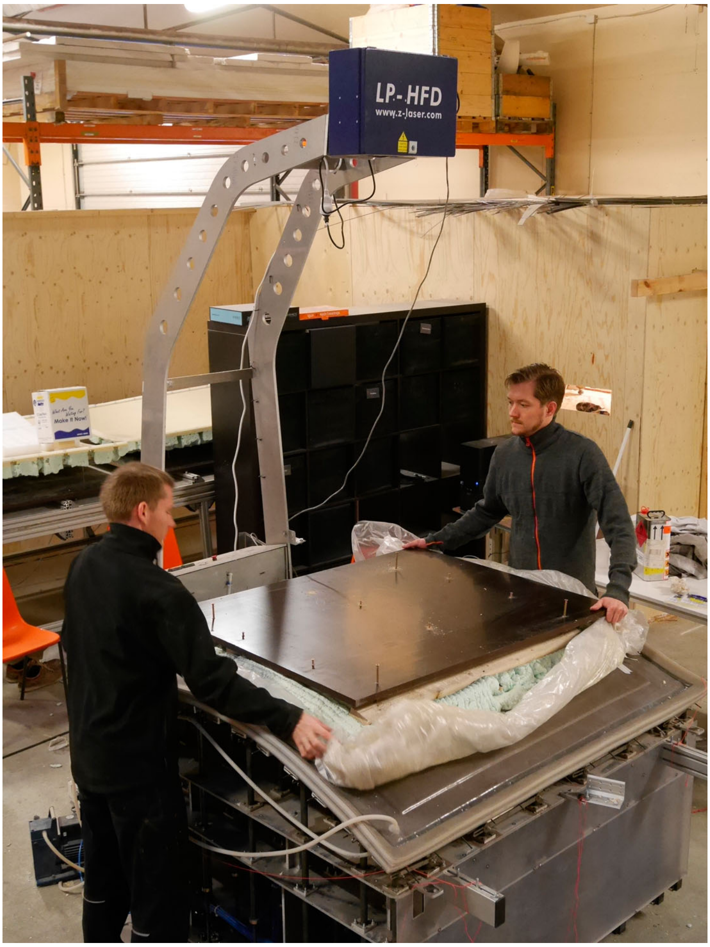

Figure 27. Final demoulding of the intermediate mould, before the edges are being trimmed and the edge-barrier being fitted.

transfer of shear forces from the hyperbolic shell to the plate. At the same time, M12 timber anchors were fixed from the underside of the timber plate to allow a secure bolted connection between the timber plate and the first ring of the hyperbolic shell. After the first ring had been connected to the timer floor plate, each additional ring of thin-walled GFRC panels was built on top of the ring below it. For the first erection of the hyperbolic shell all the holes in the GFRC panel were drilled in-situ to accommodate fabrication and installation tolerances. The installation of a panel in ring 8 is shown in Figure 37(a).

Figure 37(b,c) also show the finished hyperbolic shell from two perspectives. The installation of this thin-walled self-supporting structure has demonstrated the viability of the novel manufacturing process while utilising thin-walled GFRC in a discretized shell using sprayed GFRC with wall thicknesses of only 10 and 12 mm.

Discussions of the test phases and impact on the industry

The main recommendations from the 3 test phases were to meet the aesthetic demands for good surface quality and produce an edge-return for complex geometry thin-walled GFRC panels using the sprayed method, defined in (Henriksen et al., 2015a, 2015b). The sprayed method gave the most flexibility and the lowest material usage, while keeping the number of rejected panels to a

Figure 28. Plastic edge-barrier being fitted to the intermediate mould.

Figure 29. Finished intermediate mould ready for being tested with sprayed GFRC.

minimum. For GFRC panels larger than 2×1 m it is possible to embed the sub-structure into the panel during the spraying process to ease transport and fabrication. Adapting the new mould system originally developed for the premixed method, proposed in (Henriksen et al., 2016a) for the sprayed method, was difficult because of the constraints of the flexible table. The proposed initial solutions identified in (Henriksen et al., 2016b) only allowed a geometrically projected edge-return.

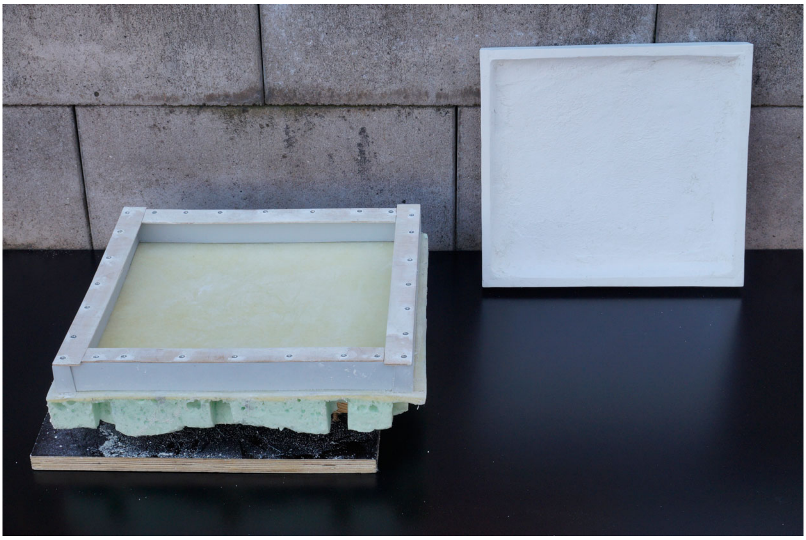

Figure 30. Intermediate mould with high edge-return.

Figure 31. Finished double curved panel with a 40 mm edge-return.

The final development of the edge-barrier shown in Figures 23 and 24 showed it was possible to devise a custom-made edge-return to meet the requirements of varying angles between the surface of the panel and the edge-return. The final development of edge-barrier using the sprayed mould system, combined with the fabrication of the double curved elements for the tower, show-cased how the new mould system could be used for the mass production of complex geometry thin-walled GFRC panels while meeting the requirements of good surface quality with an edge-return.

The cost has been the main limiting factor in realising complex geometry building envelopes using GFRC. This research will reduce the cost of complex geometry thin-walled GFRC panels by reducing the cost of the moulds by a factor of two, and the production time by approximately factor of 10, compared to if the panels were cast directly on the flexible table, to enable more

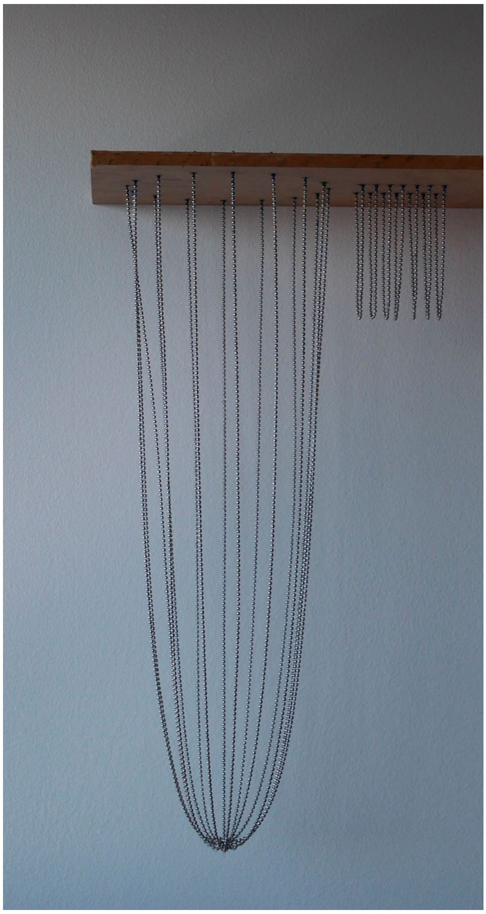

Figure 32. Catenary model of the initial design.

building envelopes with complex geometries to be realised with GFRC, rather than using alternative, less sustainable materials. To advance complex geometry thin-walled GFRC further it is also necessary to develop a digital and more automated manufacturing process and researching alternative material as thermoplastic, which could be reshaped. It has been demonstrated that this would require investment in new production plant, resulting in further reductions in the cost of manufacturing GFRC panels (Henriksen et al., 2016b).

Conclusions

This paper sought to test the viability of three different concrete production methods for a novel, complex geometry thin-walled GFRC manufacturing process. Three experimental procedures examined the main challenges encountered during the manufacture of the moulds required to fabricate complex geometry thin-walled GFRC panels. This procedure evolved into three phases where the challenges from one phase informed the development of the next phase. After the final phase III the following key contributions to knowledge emerged:

(1) The direct use of flexible tables are not suited to the large-scale automated production of complex geometry GFRC moulds.
(2) The use of a flexible table to fabricate faster-curing intermediate moulds is a more viable and cost-effective solution.

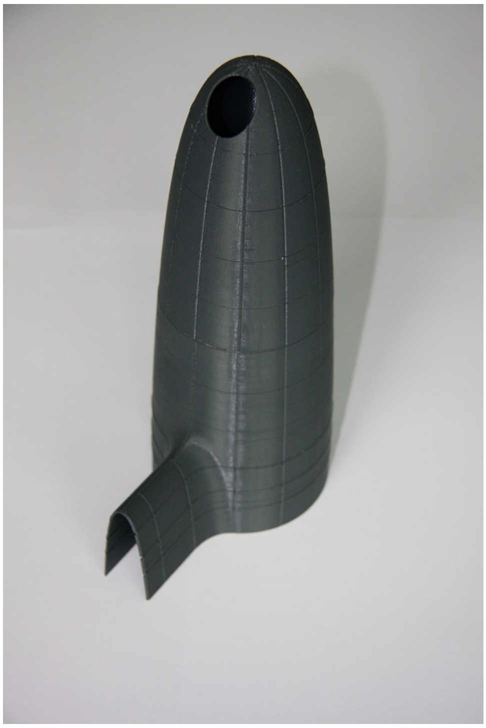

Figure 33. 3D printed thermoplastic model of the initial 1:500 scale hyperbolic shell.

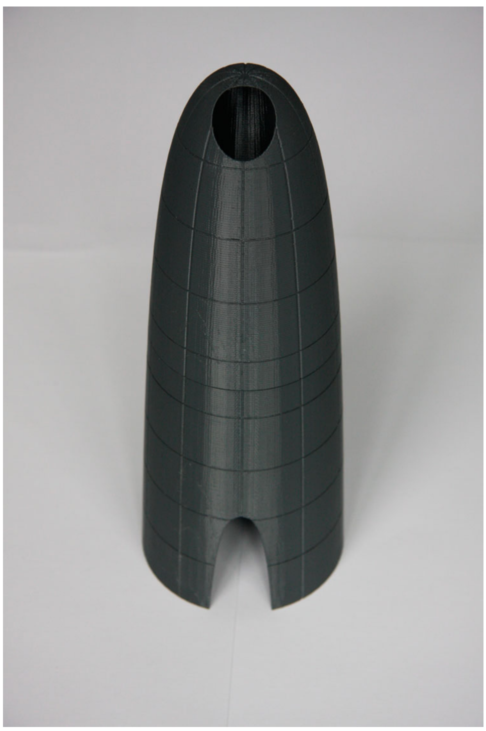

Figure 34. 3D printed thermoplastic model of the selected 1:500 scale hyperbolic shell, without entrance.

Figure 35. Intermediate mould for ring 3–9 of the thin-walled GFRC hyperbolic shell before the first casting.

Figure 36. Finished cast panels for ring 1 and ring 2.

(3) A suitable intermediate mould should be multi-layered and comprised of; a hard top-coat (to ensure good surface quality), a second HDPU layer (that is able to support the weight of the sprayed concrete panel), and a LDPU core (that is more economic than an all-HDPU mould).
(4) Such intermediate moulds allow thin-walled GFRC panels to be fabricated using the sprayed method.

A multi-layered mould was shown to be the most suitable option for the rapid and cost-effective large-scale production of complex geometry GFRC panels with the aesthetic requirements of good surface quality and edge-returns.

Figure 37. (a, b, c). Panel installation and final self-supporting hyperbolic shell in-situ.

The technical viability of this new intermediate mould for the sprayed method was established by fabricating a full-scale, self-supporting, 10 m tall, thin-walled hyperbolic shell. 9 different intermediate moulds were produced over a 9-day period. Each intermediate mould was used to cast 10 identical thin-walled double curved GFRC panels, and demonstrated that each mould could be re-used at least 10 times with sufficient robustness to allow multiple casting cycles. Fabrication of the 10 m tall thin-walled hyperbolic shell required the fabrication of 100 GFRC panels which was completed in 10 days. Achieving this using the flexible table to fabricate each GFRC panel directly would have required at least 100 days.

Due to the high costs of flexible tables (£200 k – £1 m depending on size and number of actuators) fabricators rarely have more than one single flexible table, but, as GFRC panels require up to 24 h to cure sufficiently to allow successful demoulding, each flexible table can only produce 1 GFRC panel per day. However, the novel manufacturing process presented used the flexible table as a 'mould-maker' enabling intermediate moulds to be fabricated every 2 h. This in turn allowed at least 10 uniquely shaped GFRC panels to be cast each day, compared to just one per day when casting GFRC panels directly on the flexible table.

Figure 37 *Continued*

This not only show-cased the strength of the thin-walled GFRC but the reduced production time to 10 days in total for all the panels in this structure.

The reduced cost and rapid production of this method should enable complex geometry thin-walled GFRC building envelopes to be realised where existing production methods are simply not technically or economically viable. This method would have allowed projects such as the Heydar Aliyev Center to be fabricated with complex geometry thin-walled GFRC because the project was planned initially with GFRC in mind, but was abandoned in favour of glass fibre reinforced plastic due to high manufacturing costs.

Future research

The results from Phase II identified the key challenges (**4 and 5,** Figure 5) that should be resolved to advance the intermediate mould so it can be used as part of a fully automated digital manufacturing process, as follows:

Figure 37 *Continued*

(1) The plastic edge barrier must be developed to allow for edge-returns that are greater than the panel thickness.
(2) An edge system should be developed that can accommodate the edge-return not being projected from the surface but initially being perpendicular to the surface.
(3) The compatibility challenges of the hard coat need to be identified to mitigate the problem of the air-bubbles from forming in the surface of the mould.
(4) A new flexible table should be developed that can accommodate geometries with smaller radii than 0.5 m.
(5) Reduce material use and cost.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Thomas Henriksen http://orcid.org/0000-0002-7513-2003
Ulrich Knaack http://orcid.org/0000-0001-7965-4581

References

ACI 544.1R. (1996). *State-of-the-art report on fiber reinforced concrete*. s.l.: ACI.

ACI 549.2R. (2004). *Report on thin reinforced cementitious products*. s.l.: ACI.

ACI 549.3R. (2009). *Report on glass fiber-reinforced concrete premix*. s.l.: ACI.

Alanis, E. X. D. A. (2008). *Candela*. Germany: Taschen.

Andersen, C., & Sørensen, K. (2016). *Master thesis; prototyping of reuseable double curved moulds – case study of a glass fibre reinforced concrete shell*. Aarhus: s.n.

Bekiroglu, S. (2010). *Assembling freeform buildings in precast concrete*. Delft: s.n.

Ben Allen, T. H. (2014). *Thinking space / testing space.* London: s.n.

Bentur, A., & Mindess, S. (2007). *Fibre reinforced cementitious composites* (2nd ed.). New York, UK: Taylor & Francis.

Brameshuber, W. (2006). *Textile reinforced concrete – state of the art report of Rilem TC 201 – TRC*. s.l.: Rilem Publications SARL.

Brandt, O. (2015, November 11). Interview with Ole Brandt regarding evaluation of the new mould system for sprayed thin-walled GFRC panels [Interview].

Buitelaar, P. (2004). *Ultra high performance concrete: Developments and applications during 25 years.* Kassel, Germany: Plenary Session International Symposium on UHPC.

Burry, M. (1993). *The Expiatory Church of the Sagrada Família*. London: Phaidon Press.

Castellar-Gassol, J. (1999). *Gaudí, the life of a visionary.* Barcelona: s.n.

Chilton, J. (2000). *The engineers contribution to contemporary architecture, Heinz Isler*. London: Thomas Telford.

Ferreira, J., & Branco, F. (2007). *The use of GFRC as a structural material,* s.l.: Society for Experimantal Mechanics.

FIP State of art report. (1984). *Prefabricated thin-walled concrete units*. London: Thomas Telford Ltd.

Fordyce, M., & Wodehouce, R. (1983). *GFC in buildings, a design guide for the architect and the engineer for the use of glass fibre reinforced cement in construction*. London: Butterworths.

Henriksen, T., Lo, S., & Knaack, U. (2015). *Advancing the architectural application of complex geometry GFRC*. Dubai: GRCA.

Henriksen, T., Lo, S., & Knaack, U. (2015a, May 19). Advances in the application of thin-walled glass fiber reinforced concrete elements. *Advances in Civil Engineering Materials*, *4*(1), 17.

Henriksen, T., Lo, S., & Knaack, U. (2015b, September). An innovative approach to manufacture thin-walled glass fibre reinforced concrete for tomorrow's architectural buildings envelopes with complex geometries. *Journal of Building Engineering*, *4*, 189–199.

Henriksen, T., Lo, S., & Knaack, U. (2016a, June). A new method to advance complex geometry thin-walled glass fibre reinforced concrete elements. *Journal of Building Engineering*, *6*, 243–251.

Henriksen, T., Lo, S., & Knaack, U. (2016b). The impact of a new mould system as part of a novel manufacturing process for complex geometry thin-walled GFRC. *Architectural Engineering and Design Management*, *12*, 231–249.

Isler, H. (1960). New shapes for shells. *International Association for Shell Structures*.

Lori, T. (2009). *Pier Luidi Nervi*. Milan: Motta Cultura.

MNL-128-01. (2001). *MNL-128-01 "Recommended pratice for glass fiber reinforced concrete panels"*. 4th ed. s.l.: PCI.

Raun, C. (2011, October 12). *Dynamic double-curved mould system*. Berlin, s.n.

Schipper, R., et al. (2014). Optimization of the flexible mould process for the production of double-curved concrete elements. Oslo, s.n.

Schripper, R. (2010). *A flexiable mould for double curved pre-cast concrete elements*. Delft: TUDelft.

Torroja, E. (2011, September). *The structures of Eduardo Torroja: An autobiography of an engineering accomplishment*. s.l.: s.n.

Vollers, K., & Rietbergen, D. (2007). *Adjustable mould for annealing freely curved glass panes*. Tampere, s.n.