6 Testing of solutions and proof of concept for the automated process.

Prototype test of innovative mould system for sprayed thin-walled GFRC to advance discretized shell structure that meets architecturally aesthetic demands without compromising structural integrity or buildability. This will also be proof of concept for the automation process.

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

Abstract:

Developing and testing a novel manufacturing method for thin-walled complex geometry glass fibre reinforced concrete (GFRC) panels is required to advance towards a more digital automated process. The experimental procedure described identified the main bottleneck during the manufacture of complex geometry thin-walled GFRC panels, namely, the time taken to make the mould and cast the GFRC panels. The primary outcome was the development and application of a new mould capable of casting complex geometry thin-walled GFRC panels with good surface quality using a manufacturing method that enables more rapid automated large-scale production. This intermediate mould was tested successfully using the sprayed GFRC method and was the key element during the development of a novel cost effective manufacturing method for complex geometry thin-walled GFRC panels. This method was used to manufacture 9 different double curved intermediate moulds for a 10m high GFRC self-supporting, thin-walled hyperbolic shell, with 12mm thick panels at the base of the structure. The completed structure show-cased the effectiveness of the novel manufacturing method by reducing the production time from an estimated 100 days to 10 days if using a single reconfigurable mould surface, with computer controlled actuators capable of forming free-formed geometries.

Keywords: GFRC, complex geometry, moulds, sprayed method, flexible table, hyperbolic shell.

§ 6.1 Introduction

Designing building envelopes with complex geometries using 3D CAD software has increased the demand for thin-walled glass fibre reinforced concrete (GFRC) (1) (2) (3) (4) (5) (6) (7) (8)for cladding landmark buildings and architectural infrastructure projects, (9) (10) (11). The main problems with complex geometry thin-walled GFRC panels are the time and costs associated with the production of the moulds used to cast them. Existing research about complex geometry thin-walled GFRC for architectural applications has been limited and mainly focused on the material side of GFRC and not the limitations and barriers to form complex geometry panels. Complex geometry buildings can be defined as buildings with many bespoke panels with different and changing curvature in each panel. The change in complexity ranges from flat panels, single curved, double curved and free-from panels, where free-form panels have both positive and negative Gaussian curvature in the same panel.

State-of-the-art moulds used for the manufacture of complex geometry thin-walled GFRC panels range from timber moulds to 3D CNC machined moulds. (10). The restrictions of these moulds were evaluated against the three main production methods of thin-walled GFRC panels; the automated premixed method, the premixed method and the sprayed method, to highlight the main barriers to advances in thin-walled GFRC (11). Any advances in the manufacture of complex geometry thin-walled GFRC must also meet the challenges of today's architectural demands for good surface quality and monolithic appearance. Good surface quality requires a smooth surface texture, no visual fibres in the surface, minimal air-bubbles or voids, consistent colour across all thin-walled GRFC elements and no visible cracks. A monolithic appearance may be achieved by having an edge-return to each panel making it appear thicker than it really is. Such advances not only require a more novel approach (12) but also that this approach should be fully tested. This chapter seeks to evaluate the potential limits of a novel manufacturing method for complex geometry thin-walled GFRC by realising a full-scale, 10m, self-supporting complex geometry thin-walled GFRC hyperbolic shell.

§ 6.2 Novel manufacturing process for complex geometry thin-walled GFRC

The proposed 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 (10) (11) (12) (13). The key advances of the novel method will:

- Enable thin-walled GFRC panels of more complex geometries to be produced compared to panels fabricated using existing manufacturing methods
- Lower the cost to produce complex geometry thin-walled GFRC panels
- Reduce the manufacturing time of complex geometry thin-walled GFRC panels
- Enable a fully digital manufacturing process, from initial architectural concept to installed panel
- Deliver thin-walled GFRC panels of good surface quality with edge-returns for a monolithic appearance

To develop and test this novel method it was necessary to identify and resolve the main challenges during the manufacture of the moulds when producing complex geometry thin-walled GFRC. 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. Table 6.1 shows the key phases of the experimental procedure to find a more cost effective and rapid production method. Initially the suitability of using a single reconfigurable mould surface, with computer controlled actuators capable of forming free-formed geometries (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 resulting challenges and their solution at each phase are summarised in Table 6.1. The experimental procedure evolved as the findings from phase I informed the experimental procedure for phase II, that in turn, formed the basis of the methodology for phase III.

	CHALLENGES THAT EMERGED	SOLUTION DEVISED DURING LABORATORY TESTING
Phase I: Casting GFRC on existing flexible table from automated premixed production line.		
1.	(a) Protective foil used in the automated premixed method production line wrinkles when forming double curvature concrete shapes. (Figure 2)	Devise intermediate step by utilizing the flexible table as a "mould maker". This solution is realised by using rapid curing polyurethane as the new mould material.
	(b) GFRC requires minimum 24 hours curing time on flexible table (reconfigurable mould surface, with computer controlled actuators capable of forming free-formed geometries) (14).	
Phase II: Use premixed manufacturing method so that ultra high performance concrete (UHPC) can be used for greater strengths.		
2.	(a) Low density polyurethane foam (LDPU) surface integrity not suited for use as a mould. (Figure 6)	Use high density polyurethane (HDPU) as the top surface of the new mould to ensure durability that allows the mould to be used for additional casting cycles.
3.	(b) Difficult to avoid air bubbles and voids when casting complex geometry GFRC using premixed method. (Figure 9)	Use a vacuum bag with the mould to avoid air-bubbles and voids forming in the thin-walled GFRC panel and ensure that the concrete flows to all corners of the mould.
Phase III: Use sprayed GFRC manufacturing method to produce good surface quality on complex geometry thin-walled GFRC panels.		
4.	(a) Polyurethane plastic (hard top coat) too thin, deformations in the new hard top coat from handling were easily formed.	Apply a thicker hard top coat to prevent the mould being deformed or damaged during the first casting cycles or handling of the mould.
	(b) Timber edge barrier for forming an edge-return for the thin-walled GFRC panel on the mould is difficult to use, because the GFRC is difficult to demould when cast against. (Figure 19)	Change to plastic edge barriers to allow the thin-walled GFRC panel to easily be demoulded.
5.	(a) Air bubbles with a diameter larger than 50mm forming in hard top coat leaving voids in cast GFRC surface.	Air bubbles still formed in hard coat so additional testing required to resolve this challenge.
	(b) Limitations in small radii (r>0.5m) on the flexible table.	New flexible table with more actuators with less distanced between the pistons.

TABLE 6.1 Challenges and solutions that emerged from experimental test procedures for thin-walled GFRC panels

The properties of the foam material used in the 3 phases is shown Table 6.2.

	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 tempera-ture	Celcius	55		
Compressive modulus	MPa	328		
Curing time	min	60	10	30

TABLE 6.2 Material properties for the foam material used in the 3 testing phases.

§ 6.3 Background to phase I

Manufacturing complex geometry concrete has, in the past, been dependent on timber formwork used for continuous concrete shells such as modern building envelopes designed by Torroja (15), Candela (16), Nervi (17) and Heinz Isler (18) (19). 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 numerical controlled (CNC) milling machines, it was possible to machine double curved geometries from materials other than timber. 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. (4). With the development of flexible tables (20) (14), adaptable formwork has enabled a more reusable technology. As part of this research to test a novel manufacturing method for complex geometry thin-walled GFRC, a flexible table was used at a fabrication facility using thin-walled GFRC cast on an automated premixed production line, (phase I), Figure 6.1. From this production line the premixed concrete panels were then transferred in their "greenstate" to a flexible table to cure into their final geometric form.

FIGURE 6.1 Automated production process for flat thin-walled GFRC (shown panel size ca 4m x 1.2m).

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. 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 6.2 and 6.3, (**Challenge 1a, Table 6.1**).

FIGURE 6.2 Automated premixed GFRC, (panel 1,2m x 1,2m), curing on a flexible table with the protective foil.

FIGURE 6.3 The automated premixed GFRC panel after curing and removal of protective foil. Panel is 1,2m x 1,2m.

The second key issue was the 24-hour curing time of the GFRC panel on the (costly) flexible table, so, on average only one panel could be cured on the flexible table per day. 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, Table 6.1**). Using the flexible table would create 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, (14).

§ 6.4 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, but could still utilize UHPC. The second challenge, to improve the utilization of the flexible table, required a more rapid manufacturing process, so an intermediate step was devised. This involved using the flexible table as a "mould-maker" for complex geometry forms using materials, such as a two-part polyurethane foam, with more rapid curing times, (minutes rather than hours). This enabled the premixed concrete to cure on these separate low-cost moulds, making the flexible table available to make the next mould. Phase II examined the viability of adding this intermediate step by evaluating mould materials that were not only fast-curing but would be sufficiently robust to support the premixed concrete panels. The performance criteria for suitable intermediate mould materials were identified below.

A Fast curing.
B Lightweight, with the capability to support the weight of the GFRC panels during the casting and curing process.
C Continuously good surface quality.
D Compatibility between the surface of the intermediate mould and the flexible table to ensure that the mould can be released undamaged.
E Compatibility between the intermediate mould and the uncured GFRC to ensure that the surface quality of the mould is reflected in the GFRC panel.
F Durability of the intermediate mould for multiple casting cycles.
G Recycling capability of the intermediate mould.

Different foam materials were evaluated against these requirements (12) and the materials that met most of the performance criteria, (polystyrene and polyurethane) were considered for preliminary testing. Initially, low density polyurethane (LDPU) foam was tried on the flexible table (11), and the first sample (40cm x 40cm) moulds of the resulting GFRC form are shown in Figures 6.4 and 6.5. The density of the LDPU is 18kg/m^3.

FIGURE 6.4 First sample of intermediate mould made with LDPU, (40cm x 40cm).

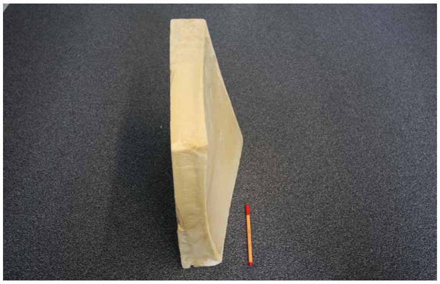

FIGURE 6.5 First sample of intermediate mould showing the double curvature of the mould, (40cm x 40cm).

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 the LDPU mould prototype showed that some of the surface of the LDPU had separated from the base material of the LDPU mould. The effects of this detached foam became visible on the surface of the concrete, as shown in Figures 6.6 and 6.7, (**Challenge 2, Table 6.1**).

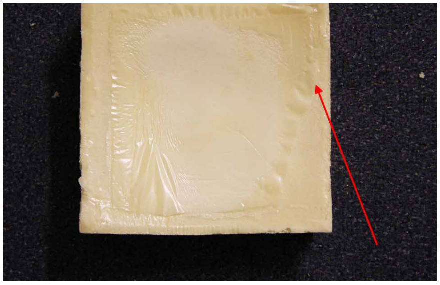

FIGURE 6.6 Intermediate mould with detached surface of LDPU foam, sample 23cm x 23cm

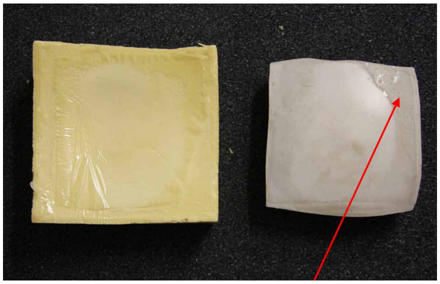

FIGURE 6.7 Premixed Concrete sample (18cm x 18cm) cast on the intermediate mould with marks from the detached surface of the LDPU foam, (23cm x 23cm)

To resolve the problems of such a non-durable LDPU foam surface, a high-density polyurethane foam, (HDPU), was considered as an alternative. The density of the HDPU is 128 kg/m^3. 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 first prototypes of the 2-layer intermediate mould were developed for the premixed method, because it also enabled UHPC to be used, allowing it's 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 6.3 summarises the advantages and disadvantages of such an intermediate mould using the premixed method.

INTERMEDIATE MOULD PREMIXED METHOD	
Advantages	Disadvantages
UHPC can be used to cast GFRC using the 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.
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.

TABLE 6.3 Advantages and disadvantages of forming an intermediate mould using the premixed method.

A small (23cm x 23cm) two-part intermediate sample mould, Figure 6.8, was tested for the premixed method.

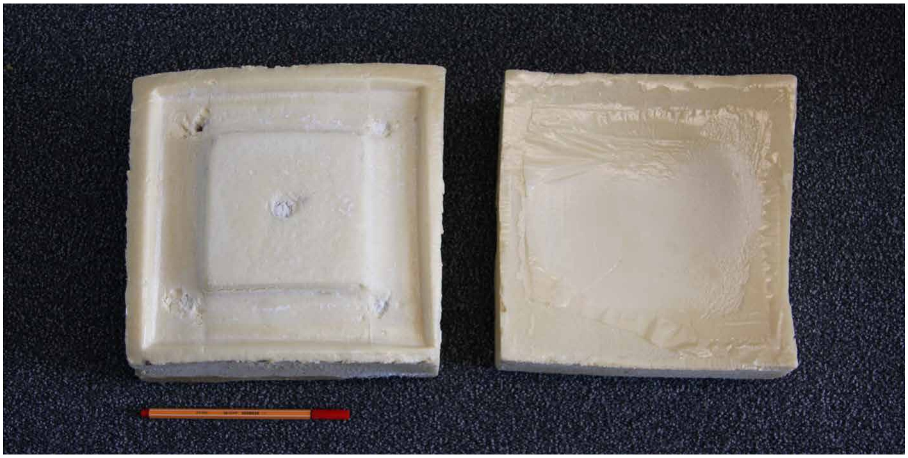

FIGURE 6.8 Small scale (23cm x 23cm) sample two-part intermediate mould for use with the premixed method.

The procedure showed that it was is possible to successfully cast prototypes with a double curved geometry and an edge-return using the premixed method. The 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 with moulds with an edge-return and the results of the tests are shown in Figure 6.9. The panel offset was not included as part of this initial test using the intermediate 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, Table 6.1**).

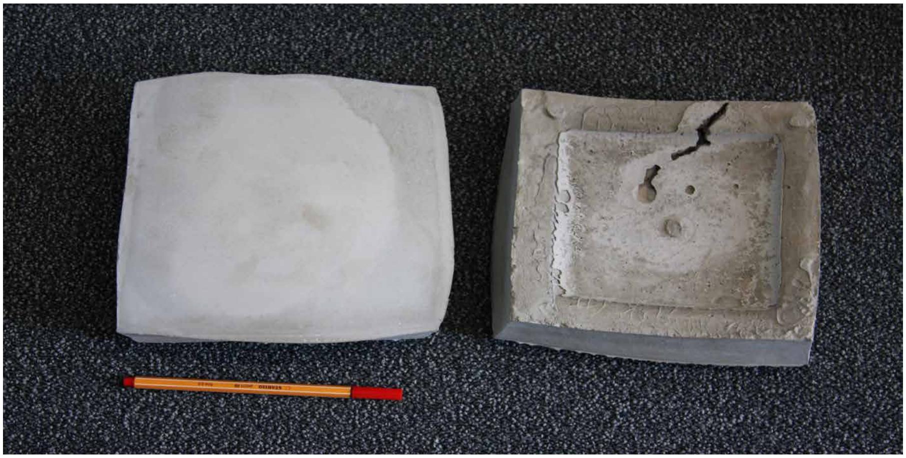

FIGURE 6.9 Premixed cast sample with small edge-return 18cm x 18cm. the challenge 2 and 3 in Table 6.1 are shown on the cast sample.

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 shaped thin-walled GFRC panels compared to the sprayed method, because:

A 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.
B 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 (11). Avoiding such voids and bubbles becomes much more challenging when casting complex geometries, ultimately leading to rejection of the panels, (Challenge 3, Table 6.1).

§ 6.5 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, phase III 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, remain. A solution was developed but it could initially only produce edge-returns that were projected from the surface.

The results of phase III would inform the manufacture of panels for a full-scale, 10m 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:

A A thin top layer of sprayable polyurethane plastic (hard top coat).
B A support layer of HDPU foam to give rigidity to the hard top coat.
C A core of LDPU foam.
D A timber edge barrier.

The demand for sharp edge-returns and panel offsets generated from the intermediate moulds are also important 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 (11). 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 complex geometry thin-walled GFRC panels with an edge-return and a panel offset (11). The outcome of the experimental procedure confirmed this to be the case.

A solution to utilize the flexible table to make an intermediate mould with the sprayed method was developed (12). 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 6.4.

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	

TABLE 6.4 Advantages and disadvantages of the intermediate mould for the sprayed method

The first prototype to combine the new mould build-up developed from phase II, using a hard top coat on top of the HDPU foam, all sprayed with a designated tool, is shown in Figures 6.10 to 6.13. The shape is a double curved geometry with the smallest radius being 1.5m.

FIGURE 6.10 Setting out of the tested mould shape on the flexible table and adding the first layers, panels size 1m x 0.5m

FIGURE 6.11 Curing of the HDPU foam on the flexible table

FIGURE 6.12 Curing the LDPU on the flexible table

FIGURE 6.13 Fitting timber edges barriers on the mould

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

A second prototype was made for a (more complex) free-form geometry (11). The manufacturing stages for the second prototype are shown in Figures 6.14 – 6.17.

FIGURE 6.14 Setting out of the tested mould shape on the flexible table

FIGURE 6.15 Applying the hard coat

FIGURE 6.16 Applying the HDPU

FIGURE 6.17 Fitting edges on the mould

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 6.17.

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

A Project the shape on the flexible table.
B Outline the edges with a removable tape and foil.
C Apply the releasing agent.
D Spray the hard coat.
E Spray the HDPU foam and allow it to cure.
F Spray the LDPU foam.
G Attach the timber base.
H ch the timber edge-barriers.
I Trim the unnecessary foam from the edge of the panel.

§ 6.5.1 Testing the intermediate mould for the sprayed (GFRC) method

The first and second prototype intermediate mould for the sprayed method was evaluated by an experienced fabricator of thin-walled GFRC (21) 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, (**Challenge 4a, Table 6.1**).

The prototypes for the sprayed method were tested with normal sprayed GFRC and was sprayed and compressed as described in (10). Figure 6.18 shows the newly sprayed GFRC being compressed with rollers.

FIGURE 6.18 The finished sprayed GFRC being compressed with rollers to mitigate voids and air-bubbled in the GFRC.

FIGURE 6.19 Demoulding of the free-form prototype.

FIGURE 6.20 The finished free-form GFRC panel after demoulding.

Figures 6.18 – 6.20 show that it was possible to successfully cast and de-mould the GFRC using the new intermediate mould, however, the edge barrier of the intermediate mould was made out of a timber and was difficult to de-mould without damaging the thin-walled GFRC panel, (**Challenge 4b, Table 6.1**).
Figure 6.19 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 poly ethylene (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 6.20.

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<1m) with a constant curvature and small edge-returns. This depends on their thickness as smaller edge barriers produce the size of the edge-return may be curved to make smaller radii.

FIGURE 6.21 The simplified timber base plate being fitted to the foam part of the intermediate mould.

FIGURE 6.22 Final demoulding of the intermediate mould, before the edges are being trimmed and the edge-barrier being fitted.

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 6.21. Figure 6.22 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 6.23 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.

FIGURE 6.23 Plastic edge-barrier being fitted to the intermediate mould.

FIGURE 6.24 Finished intermediate mould ready for being tested with sprayed GFRC.

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 6.24. 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), 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 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 (13). The cost of single intermediate moulds when commercialized was projected to be approximately 250 Euro/m^2 (13), 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 0.5m x 0.5m sample was made to demonstrate an edge-return. The edge-barrier used for the small test was thicker (40mm) than the 10mm hard (Shore 80) silicone based barrier used for prototype 3 as shown in Figure 6.25.

FIGURE 6.25 Intermediate mould with high edge-return

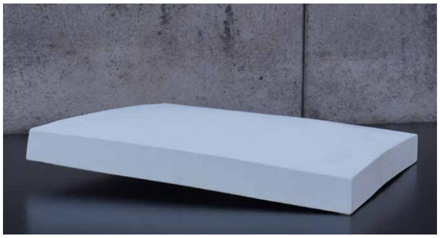

FIGURE 6.26 Finished double curved panel with a 40mm edge-return

The intermediate mould with the 40mm edge-barrier was successfully tested with the sprayed method, as shown in Figure 6.26; demonstrating that 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 utilized fully compared to the sprayed method.

§ 6.6 Designing a thin-walled 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 would be used to fabricate a complex geometry thin-walled hyperbolic shell, comprised of double curved panels, as shown in Figures 6.27 – 6.29. A thin-walled GFRC self-supporting hyperbolic shell was developed by Thomas Henriksen and the architect Ben Allen for a design competition (22). This structure was based on a hyperbolic shape used by Antony Gaudi for the Church, La Sagrada Familia in Barcelona (23) (24), selected for being a perfect compression form when turned upside down. Unfortunately the competition was unsuccessful so it was decided to build the hyperbolic shell as part of research collaboration between TUDelft, TUDarmstadt and Aarhus University. Figure 6.27 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 6.28, but was removed as the design evolved to reduce the number of different panels. Figure 6.29 shows the final form of this hyperbolic shell, printed as a 1:500 scale 3D thermoplastic model before manufacture.

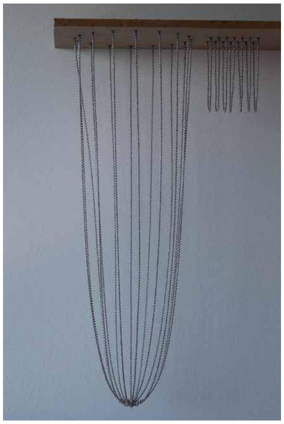

FIGURE 6.27 Catenary model of the initial design.

FIGURE 6.28 3D printed thermo-plastic model of the initial 1:500 scale hyperbolic shell.

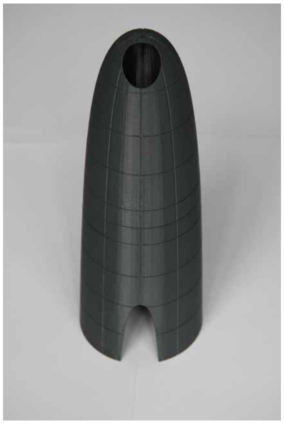

FIGURE 6.29 3D printed thermo-plastic model of the selected 1:500 scale hyperbolic shell.

The hyperbolic shell (18) (19) 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 1.2m x 1.2m 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 (25).

§ 6.7 Testing of 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 12mm for the panels in the bottom two rings with a limit of proportionality (LOP) (26) of 11 MPa, was sufficient, and a wall thickness of 10mm was sufficient for the panels in the remaining rings of the hyperbolic shell. The connection detail between the panels were sized as part of an FEM analysis, and showed that connection could be achieved successfully with standard M12 bolts (25) (27). To maintain the rigidity of the connection and buckling capacity of these thin-walled GFRC panels, a connection with 10mm thick GFRC panel was tested for it's tensile capacity with two 2mm stainless steel lash plates, (since only the bottom two rings were made of 12mm thick GFRC). The tensile test showed that the capacity of the 10mm 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 6.4kN. The design load for each bolt connection in the most critical connection was calculated to be 3kN, so the connection capacity of the discretised thin-walled self-supporting GFRC hyperbolic shell was utilised by less than 50% (25) (27).

§ 6.8 Manufacture of intermediate mould for thin-walled GFRC Sculpture

To manufacture the thin-walled GFRC panels, 9 different intermediate moulds were produced for each ring of the hyperbolic shell, with 10 identical panels in each ring. This allowed each intermediate mould to be reused 10 times. The intermediate moulds were produced as shown previously in Figures 6.21 - 6.24.

FIGURE 6.30 Intermediate moulds for ring 3-9 of the thin-walled GFRC hyperbolic shell before the first casting.

FIGURE 6.31 Finished cast panels for ring 1 and ring 2.

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, Table 6.1**). 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. It should be possible to mitigate the air bubbles formed in the hard top coat, 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, Table 6.1**). This challenge could, in future, be met by building a new flexible table with more actuators and more closely spaced pistons. The intermediate moulds for ring 3-9 of the thin-walled GFRC hyperbolic shell before the first casting and finished cast panels for ring 1 and ring 2 are shown in Figure 6.30 and Figure 6.31.

§ 6.9 Installation of thin-walled GFRC self-supporting hyperbolic shell

The installation of the thin-walled GFRC self-supporting hyperbolic shell was made 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 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 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 6.32.

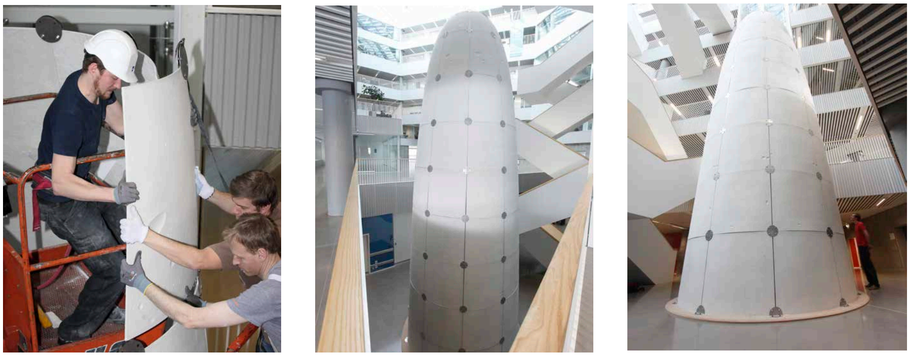

FIGURE 6.32 Panel installation and final self-supporting hyperbolic shell in-situ.

The finished hyperbolic shell from two perspectives is also shown in Figure 6.32. 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 10mm and 12mm. The hyperbolic shell was erected over 3 days and was completed on February 12th 2016.

§ 6.10 Recommendations from the test phases and impact on the industry

The main recommendations from the 3 test phases are to meet the aesthetic demands defined in (10) (11), for good surface quality and produce an edge-return for complex geometry thin-walled GFRC panels using the sprayed method. The sprayed method gives the most flexibility and the lowest material usage, while keeping the number of rejected panels to a minimum. For GFRC panels larger than 2m x 1m it is possible to embed the sub-structure into the panel during the spraying process. Adapting the new mould system originally developed for the premixed method, proposed in (13) for the sprayed method was difficult because of the constraints of the flexible table, and the proposed initial solutions identified in (12) only allowed a geometrically projected edge-return. The final development of the edge-barrier shown in Figure 6.25 shows it is possible to make 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 and enable more building envelopes with complex geometries to be realised with GFRC, rather than alternative, less sustainable materials. To advance complex geometry thin-walled GFRC further it is also necessary to develop a digital and fully automated manufacturing process. In (12) it was demonstrated that this would require investment in new production plant, but would result in further reductions in the cost of manufacturing GFRC panels, compared to using the sprayed method with the new mould system.

§ 6.11 Further research

The results from Phase II identified the key challenges (**4 and 5, Table 6.1**) 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:

A The plastic edge barrier must be developed to allow for edge-returns that are greater than the panel thickness.
B 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.
C 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.
D A new flexible table should be developed that can accommodate geometries with smaller radii than 0.5m.
E Reduce material use and cost.

§ 6.12 Conclusion

This chapter 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:

A The direct use of flexible tables are not suited to the large-scale automated production of complex geometry GFRC moulds.
B The use of a flexible table to fabricate faster-curing intermediate moulds is a viable solution.
C A suitable intermediate mould is 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).
D 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.

The technical viability of this new intermediate mould for the sprayed method was established by fabricating a full-scale, self-supporting, 10m 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 demonstrate that each mould could be re-used at least 10 times with sufficient robustness to allow multiple casting cycles. This process allowed the 10m tall, self-supporting thin-walled hyperbolic shell to be fabricated in 10-days, with 12mm thin-walled GFRC panels at the base. This not only show-cased the strength of the thin-walled GFRC but the reduced production time of 10 days in total for all the panels in this structure. An equivalent structure using a single flexible table in the conventional manner would have taken an estimated 100 days to complete.

Fabricating the hyperbolic shell demonstrated the viability of this novel method for manufacturing complex geometry thin-walled GFRC. 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 allow 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.

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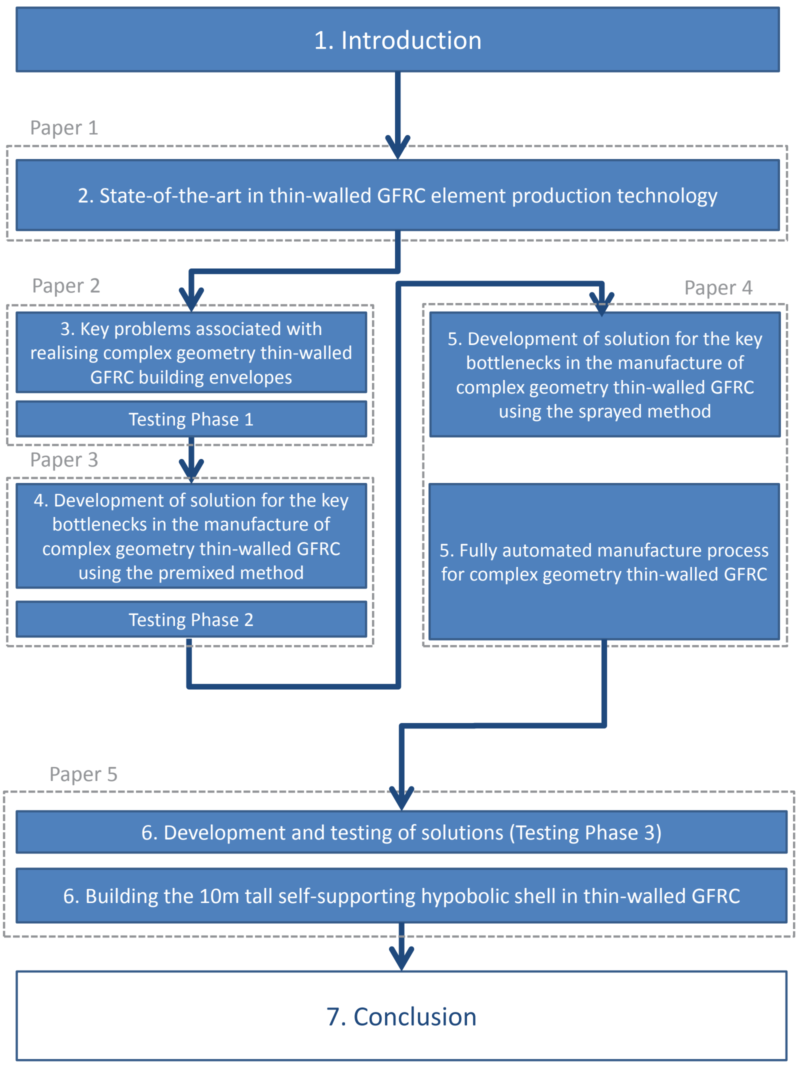
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