5 Developing a solution for the sprayed concrete method and proposing automated process.

Innovative automated mould system for sprayed thin-walled GFRC for a more streamlined digital detailed design iteration process with reduced environmental impact.

The impact of a new mould system as part of a novel manufacturing process for complex geometry thin-walled GFRC.

Abstract:
Resolving the challenges of advancing thin-walled glass fibre reinforced concrete (GFRC) requires a novel, more automated digital design and manufacturing process that meets the requirements of present demands for thin-walled GFRC panels. The design, optimisation and manufacture of moulds using existing approaches is subject to many limitations and constraints that result in feedback loops between each stage of the design and manufacturing processes. This precludes the efficient and fully automated digital design and manufacture of complex geometry thin-walled GFRC panels. The proposed mould system overcomes many of these constraints, and when combined with new software plug-ins, will be capable of digitally resolving the limitations or constraints that interrupt each key stage of the design and manufacturing processes. These plug-ins have been characterized to provide a seamless interface between software and hardware with minimal delays caused by design feedback loops to allow a fully automated digital design process to be realised. The impact of the new mould on this novel process is analysed and further research necessary to advance the process is identified.

Keywords: GFRC, GRC, FRC, Complex, geometry, moulds, sprayed, premixed, manufacturing, process

§ 5.1 Introduction

The design of complex geometry thin-walled glass fibre reinforced concrete (GFRC) panels, (an introduction to the topic of thin-walled GFRC and the current limitation and the background for this research can be found in (1) (2) (3)), and the subsequent manufacture of the individual panels, are currently separate stages that are not integrated and optimized into a fully digital and automated process. This chapter seeks to address the key research questions that will resolve this problem, namely:

1. What are the current constraints in the design and manufacturing processes that limit advances in complex geometry GFRC?
2. What are the barriers to a more automated digital design and manufacturing process for complex geometry GFRC?

The research was undertaken in three stages:

1. Interviews with key industry persons with visits to leading manufacturers to identify the constraints and barriers.
2. Two research building projects were examined as case studies to define the process and to identify the key feedback loops.
3. A new method to produce moulds for the sprayed thin-walled GFRC was tested in a laboratory and will be developed into a full-scale prototype in future research.

This paper aims to highlight the necessary processes required to advance complex geometry thin-walled GFRC beyond the limitations of their current application and utilization. A general introduction to thin-walled walled GFRC can be found in (4) (5) (6) (7) (8) (9).

§ 5.2 Constraints in the design and manufacturing processes that limit advances in complex geometry GFRC.

The manufacturing technology for thin-walled GFRC has not developed at the same pace as 3D CAD software (10) (11) (2), and the individual production methods used, (sprayed, premixed and automated premixed) each have limitations that prevent them from being developed beyond their existing specific applications (1) (5). The development of the design stages is pre- level-1 BIM and usually undertaken in different 3D CAD software packages unable to speak the same "language", as some are open source, while others are commercially restricted software.

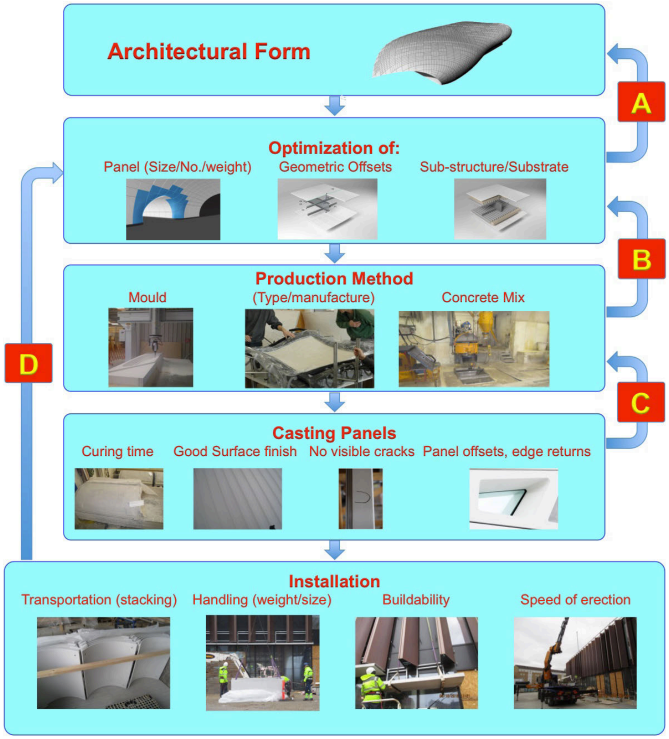
To advance the manufacturing stage of the design process a new mould system adapted to allow future "printed" GFRC fabrication has been developed and tested to assess it's suitability to the process. In addition, current mould materials based on non-recyclable foam materials were re-evaluated for their environmental impact on the industry to identify the steps necessary to advance this process further.

§ 5.3 Barriers to a more automated digital design and manufacturing process for complex geometry GFRC.

At the initial architectural design stages the building geometry is developed as a smooth continuous surface without any detailed definition of panelization, joint-widths or geometric offsets (2) (12). Current production methods for complex geometry thin-walled GFRC are produced from drawings developed at the detailed design phase and little information regarding the production limitations are available.

The missing information about panelization, joint-widths and geometric offsets, prevents the initial design stage from being progressed and results in an iterative feedback loop. This also applies to the detailed design stage where the panelization and geometric offsets must be known before the most appropriate production method for the GFRC panels may be selected. The choice of production method also determines the maximum allowable panel sizes that may be fabricated and geometric offsets that may be applied. Such barriers to the design process drive the overall cost and, in most cases, leads to extensive value engineering and cost cutting, resulting in the geometry of the GFRC envelope being simplified down to facetted solutions, or being resolved using an alternative more cost effective material.

The design and manufacturing challenges at this stage require the current productions methods, (sprayed, premixed and automated premixed) to be adapted to the detailed design development, because the available panel dimensions and build-up of the GFRC panels determine their connection to the sub-structure or the sub-structure that is embedded in the GFRC (1) (13) (14) (6). For each production method there is typically a different connection detail between the GFRC element and the substrate. Since this exact information is not available at the design phase this has an impact later when the production method is chosen and could lead to a redesign. Without such detailed information throughout the design stages the overall process is prolonged due to the iterative design feedback loops A to D, as shown in Figure 5.1.



	Feedback loops that delay realizing complex geometry GFRC Architectural forms
A	The initial design of the Architectural form is restricted by the limits of panelization, geometric offsets and build-up of the sub-structure/substrate
B	The panel size, geometric offsets and sub-structure/substrate build-up, must be matched to the appropriate production methods, while also accommodating the consequences of material properties on the panelization/geometric offset and sub-structure/substrate.
C	The material behaviour during the casting process determines allowable production methods for the panels.
D	The transportation, handling and buildability of the GFRC panels restrict the panelization/geometric offset and sub-structure/substrate

FIGURE 5.1 Barriers to realizing complex geometry GFRC architectural forms due to iterative design feedback loops and how the proposed fully digital automated process resolves the delays and iterations.

Each feedback loop that interrupts the key stages of the design and manufacturing processes for complex geometry thin-walled GFRC panels has been identified to show where specific software plug-in interfaces may be embedded into conventional 3D CAD software (11). Resolving each limitation and constraint to reduce or eliminate feedback loops A to D will provide a more seamless interface between software and hardware at these key stages and help to realise a fully automated digital design and manufacturing process. The detailed development of these plug-in falls outside the scope of this research, however the functional requirements of each plug-in has been characterized.

§ 5.4 Challenges that need to be addressed before advancing to an innovative fully automated and digital manufacture process for thin-walled GFRC panels.

To realise a faster and more cost-effective, fully automated thin-walled GFRC manufacturing process it is necessary to identify the main drivers and their associated delays during the entire process from the concept design stage to manufacture and installation. The five main stages of the design & manufacturing process that are delayed by iterative design feedback loops A to D (Figure 5.1) are:

1. Determining the architectural form
2. Optimisation of panel size/weight, geometric offsets and appropriate sub-structure/substrate
3. Identifying the most appropriate production method
4. Casting the panels with the required offsets and surface finish
5. Transportation, installation and handling on site

Each of these five stages are interconnected and directly influence each other, so any delays from iterative design feedback loops A to D prolong the whole process and increase time and costs.

Loop A represents the need to change the initial design of the architectural form so that it meets the limitations imposed by panelization, geometric offset and build-up of the sub-structure and substrate.

Loop B represents the iterations required to match the panel size, geometric offsets and sub-structure/substrate build-up, to the appropriate production methods, while also accommodating the consequences of material properties on the panelization, geometric offset and sub-structure/substrate.

Loop C indicates how material behaviour during the casting process determines allowable production methods for the panels.

Loop D represents how transport, handling and buildability restrict the panelization, geometric offset and sub-structure/substrate, potentially delaying or halting the whole process.

§ 5.4.1 The challenges imposed by the architectural form

During the concept design stage the architectural form of the building envelope geometry is represented by a 3D surface and is comprised of a continuous surface without any panelization. Initially the surface has no real thickness and the geometric offsets to the main structure or sub-structure have yet to be defined, as shown by an example of a free-form roof surface in Figure 5.2.

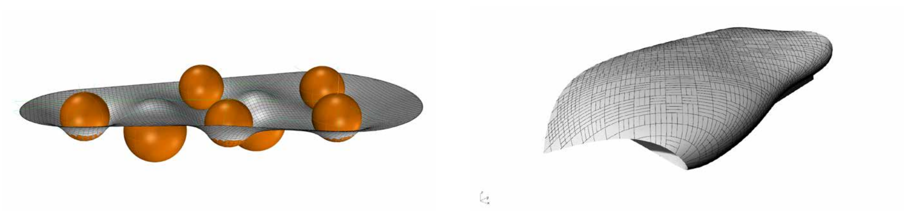


FIGURE 5.2 Initial generation of a free-form architectural shape and free-form architectural shape for a roof proposed to be built with GFRC

The free-form surface forms the basis for the next steps in the design process, the panelization, Figure 5.2, and determining the geometric offset and build-up of the sub-structure/substrate. For the Architectural form, 2D detail drawings are produced to show the interface between the panels and the substrate, to determine the design intent of the interface. This architectural form is merely a 'surface' without information about the build-up of the super-structure or weather-tightness layers, thereby placing restrictions on the architectural intent.

§ 5.4.2 Optimisation of panels, geometric offset and sub-structure/substrate

The panelization, the geometric offset and the build-up of the sub-structure/substrate for a complex geometry envelope are 3 inter-connected design tasks influenced not only by each other but by the consequences of decisions made later regarding the appropriate production method and the installation stages as shown in figure 5.1.

Panel optimization is comprised of two key elements:

A. The architectural intent: Often fewer large panels are desirable to realise a seamless monolithic architectural form, and depends on the size of the building. This demands fewer, but more complex geometry, large and heavy panels that introduce transportation issues. Conversely panelization with smaller panels eases the demands on manufacturing but compromise the aesthetic purity of the design intent. The panelization usually follows geometric rules, such that geometries are made from a traceable geometry, i.e. a cut torus (15). However if the geometry is a free-form surface[4] then the panelization has to be implemented by adding cut lines in an almost perpendicular grid.

B. The panel detailing: i.e. deciding on an acceptable joint width between panels and the depth of the panels. During detailed panelization, edge-returns and panel offsets are introduced, (2), to give the impression of perceived depth and a more monolithic appearance (16). The same also applies for the unique panels at the edge of the surface. Here panels might be too small to manufacture or the panels become oversized which means that an additional split line needs to be introduced, locally, in the panel. Small joint widths are often demanded to give a more seamless appearance.

Figure 5.3 show two different panel configurations for the same roof. The first shows a greater number of smaller panels ranging from 1m x 1m to 3m x 3m, excluding the unique panels at the roof edge. The second shows the same architectural geometry with fewer larger 3m x 3m panels excluding the unique panels at the roof edge.

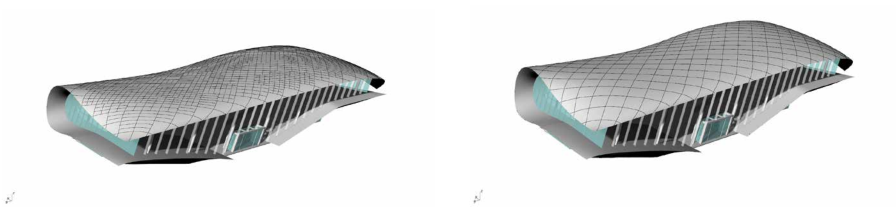


FIGURE 5.3 Visual consequences of panel size on architectural form

The detailed panelization process seeks to determine the most acceptable compromise between panel configuration while retaining the purity of the architectural form, shown as design iteration loop A in Figure 5.1.

A geometric offset (12), is defined as a parallel offset of the surface and describes the space between the outside surface of the GFRC panel and the over-side of the main structure. The geometric offset is comprised into the following elements;

4 Free-form surface both have a positive and negative Gaussian curvature in the same surface (26)

- GFRC panel thickness
- GFRC edge-return and panel offsets (Not the same as an geometric offset)
- GFRC sub-structure / connectors
- Secondary structure (Substrate)
- Membrane / insulation (Substrate)
- Main structure (Substrate)

The build-up of a roof including the suspended ceiling is shown in Figure 5.4.

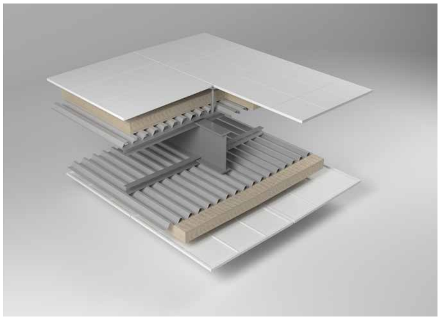


FIGURE 5.4 Geometric Offset

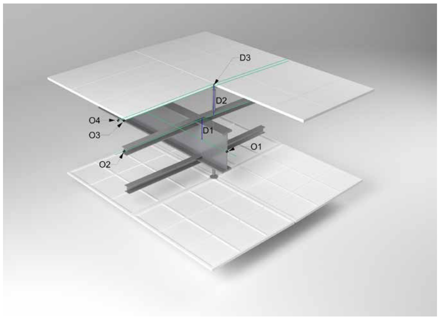


FIGURE 5.5 Geometric Offset with GFRC Panel in place.

For a complex geometry free-form building envelope the geometric offset is vital to understanding the details that need to be developed to enable the manufacture and installation of the GFRC panels. Figure 5.4 shows an example of a geometric offset with the GFRC panel in place, the edge-return of the panel and the connectors, the secondary structure, the membrane, the insulation and the main structure. The substrate is defined as the secondary structure, the membrane/insulation and main structure. The offset lines and the distances are described as;

- The O1 line is the centreline of the main steel.
- The O2 line is the centreline of the secondary steel
- The O3 line is the underside of the edge-return,
- The O4 line defines the top surface of the GFRC,
- The D1, D2 and D3 are the distances between the offsets.

Figure 5.5 shows a planar build-up, however, if the top surface is curved the geometric offset lines become more complex with greater offsets. In the worst cases this requires a support structure that cannot be manufactured to meet the tolerance boundaries of the GFRC panels. Geometric offsets for GFRC build-ups are generally a challenge if windows have to be built into the surface, making the detailing around the window very complex. This is complicated for facetted surfaces, but, for curved and double curved surfaces this becomes an even greater challenge in terms of buildability.

When a geometric offset is added to the architectural surface and combined with a 3D model of the main structure, any clashes between the geometric offset and the main structure will become apparent. Such clashes are often overlaps of the different building elements in the 3D models when they are combined. Resolving these clashes requires the main structure to be changed or more likely the architectural form must be revised to allow for the build-up. This also contributes to feedback loop A in Figure 5.1, requiring amendments to the architectural form, and the design process must re-commence. This design feedback loop continues until there are no more clashes.

The build-up of the substrate is defined by the elements that are not integrated into the GFRC panels but forms part of the space in-between the main structure and the GFRC element. This is mainly the secondary structure if it is not integrated into the GFRC elements. In most cases the secondary structure is cast into the sprayed GFRC panels (13) (14) (6). The insulation and membranes, or in some cases, a standing seam roof, forms the elements between the main (primary) structure and the secondary structure[5]. This build up is important since the GFRC panels in most instances act as rainscreen panels.

The process of the panelization, determining the geometric offset and the build-up of the substrate are inter-connected. However, the initial panelization is normally undertaken along with the development of the architectural form but when geometric offsets are being applied, (creating the distances for the different elements of the build-up), the outcome may result in an additional panelization loop, required to fit the panels and achieve the correct joint lines. The geometric offset and build-up of the sub-structure/substrate can only be resolved if the appropriate production method that defines the GFRC panel thickness and type of sub-structure is used, and which installation method is deployed to mount the panels.

All three processes have to be considered simultaneously. A fully automated process would allow the limitations of the production method and the installation to be considered as a variable at the detailed design stage. This would reduce the delays caused by feedback loops A and B in Figure 5.1, by incorporating the limitations into a software plug-in, used when generating the panelization and geometric offset.

5 The connection between the main structure and the secondary structure penetrates the vapour line, which needs to be sealed against water ingress if a membrane solution is used. In the case of the membrane, then it is prone to being perforated leading to leakage, and the number of connections penetrating the membrane should be kept to a minimum. However, this requires fewer larger GFRC panels and in some cases introduces greater panel weight per m^2. If a standing seam roof is used, penetrations can be avoided but the standing seam roof has limited capacity with regards to the load that can be fixed to the standing seam.

§ 5.4.3 Most appropriate production methods

The selected production method for GFRC is fundamental to the design process of a complex geometry because it determines the permitted level of complexity of the architectural form at the conceptual design stage, the degree of panelization required, and, the build-up of the substrate. The main production methods, (the sprayed method, premixed method and the automated premixed method) each have different advantages and material limitations (1).

Sprayed GFRC is labour intensive and requires skilled workmanship. Premixed concrete has a reduced fibre content, with uncontrolled fibre orientation, and is difficult to apply to curved geometries without a vacuum system or forming the concrete in it's "greenstate" (1) (17) (3). Both are therefore costly to implement on large projects with complex geometries.

For automated premixed GFRC the production lines are designed to produce flat sheets that may be formed in their "greenstate" (18) for the intended geometries, however, this is currently restricted to single curved geometries. If producing double curved and free-form geometries the automated premixed sheet will result in folds when positioned on a double-curved or free-form mould.

Key production issues that currently prevent a fully automated process are:

- Only flat and single curved geometries are possible
- Limited production sizes in current automated productions lines
- Limited flexural strength
- Sub-structure/substrate needs to be embedded into the GFRC panel
- Edge-returns and panel offsets cannot be produced

To advance the production methods towards a fully automated and digital process the advantages of the sprayed and premixed method must be combined as part of an automated process line.

§ 5.4.4 Casting methods and final surface finish and quality

The current manufacturing techniques for double curved and free-form complex geometries utilise computer numerically controlled (CNC) milling machines to produce the moulds for the production of each GFRC element (19) (20). This method has limitations due to the extended production time, the high cost of producing the moulds, and the difficulties in achieving the desired surface quality.

Another barrier in detailed design iteration (Loop B) is a full understanding of the production method being used, the joint sizes, and the geometric offsets to be determined, before the detailed design of the architectural shape may be progressed. In addition it is necessary to resolve the current mould restrictions at loops A, B and C in Figure 5.1 because there is a limit to the maximum mould dimensions and the change in curvature that existing flexible tables can generate (21) (22).

The quality of the finished GFRC panels are linked to how they are cast, in particular the quality of the mould, the method of de-moulding, the initial 24hr cure before de-moulding, and the 28-day cure period. Limitations today are the costly and time consuming process of making CNC machined foam, or wooden, double curved moulds, with little or no, repetition, (19) (20). For curvatures with large radii it is possible to use big steel or wooden plates and bend panels into place, thus creating the surface. The CNC moulds must have a high quality surface finish otherwise any discontinuities will be visible in the finished concrete surface, potentially leading to rejection of the panel.

To advance to a fully automated and digital design and manufacturing process requires a new automated mould system that can be integrated into the process. The proposed novel manufacturing process achieves this by combining the advantages of the 3 main manufacturing methods into a mould system that:

- Can easily generate a full range of complex mould geometries, (desired curvatures, panels sizes, while meeting the requirements for edge-returns and panel offsets).
- Can apply layers of meshed fibre reinforcements that are shaped to match the individual curvature of the panel with a sprayed GFRC mix.
- Has a faster production speed at the main bottleneck, i.e. the production of the moulds.

Resolving these limitations will reduce/minimize the delays caused by iterative design loops A-C in Figure 5.1 and move towards the ultimate goal of a complex geometry thin-walled GFRC "Printer".

§ 5.4.5 Installation on site

Installation of complex geometry GFRC panels is the final stage that must be considered as part of a fully automated and digital design process. Panel sizes using current automated process lines are limited to widths of approximately 1.2m and lengths of 4m (18). However, due to the limited thickness of the automated premixed panels a sub-structure needs to be added to avoid the panels from breaking during handling and transportation. For panels larger than 3m x 3m produced with the sprayed or premixed method, a sub-structure must be embedded into the panel, however, they can only be transported if the GFRC panels do not exceed dimensions that can be transported in customised trucks, (very costly) or shipped as bulk cargo. If panel sizes determined at the concept design phase are too large to be installed, feedback loop D, Figure 5.1, involves re-penalization resulting in revised panel sizes. Conversely, if the panel sizes in the initial concept phase are too small, larger panels may be considered to reduce the time taken during the installation phase. The greatest current limitation during installation is the fixing method between the complex shaped GFRC panel and the sub-structure, to ensure that the fixings of the GFRC are not visible. If the panels are small (weighing less than 50kg[6]) and can be man-handled on site, it is easier to fix the panels to the sub-structure. For larger sizes e.g. 3m x 2m panels or larger, the panels need to be installed with machinery that can handle the panels on-site without damaging the edges of the GFRC panels. This means that lifting points need to be cast into the GFRC elements. For soffit panels that are oversized, specialised non-standard lifting equipment is required, making them difficult to install. “Jumbo” size panels larger than 3m x 3m usually require the sub-structure to be embedded into the panels. Normally such panels have a geometric offset from the main structure that is usually large enough to work behind the GFRC panel and make the connection between the GFRC panel sub-structure and the main structure. To enable handling and installation the proposed novel process must include a fixing system that allows the fabrication tolerances of the GFRC panel, and the installation tolerances on-site, to be simultaneously accommodated.

6 It is assumed that 2 people are allowed to carry 50kg, based on this it would be possible for 2 people to man-handle a 50kg GFRC panel without heavy machinery.

§ 5.5 Developing a novel fully automated and digital design and manufacturing process for complex geometry thin-walled GFRC.

To develop a fully automated and digital design and manufacturing process for thin-walled GFRC, feedback loops A to D shown in Figure 5.1, must be minimised or ideally eliminated. The proposed methodology achieves this through the use of software plug-ins to resolve each feedback loop. At the initial design stage, a plug-in can embed the information from the production limitations into the development of the architectural form, the panelization, the geometric offset, and the build-up of the sub-structure/substrate. Current production knowledge allows non-conformity in the rationalized surface to be identified resulting in a revised building form, and re-panelization of the surface to inform feedback loops A and B in figure 1. One of the key barriers here is the current mis-match in the “languages” between the different design software platforms used today, namely, the 4 separate software platforms for each of the following 4 stages:

1. The architectural form
2. Optimisations and rationalization
3. Digitization, digital input to allow production
4. The production process.

Currently an integrated modelling process requires a different geometric model to be created at each stage. This problem exists mainly because standard commercial software solutions are not able to resolve the non-uniform nature of building design. This is one of the key barriers to a fully automated and digital process for complex geometry GFRC, and is outlined in table 5.1.

ITERATIVE DESIGN FEEDBACK LOOP	LIMITATIONS AND RESTRAINTS THAT PREVENT THE PROCESS FROM BECOMING A FULLY AUTOMATIC PROCESS	HOW THE LIMITATIONS MAY BE RESOLVED TO ALLOW A FULLY AUTOMATED AND DIGITAL DESIGN AND MANUFACTURING PROCESS.
A	Different software "languages" between the initial design and the detailed design stage. Missing information about production restraints at the initial design stage. Defining the panel size and joint widths influences the architectural form. The geometric offsetting of the panels influences the architectural form. The build-up of the substrate influences the architectural form.	Development of a software plug-in embedded with panel optimization information in a common software language.
B	Different software "languages" between the detailed design and the digital input necessary for an automatic production line. The selection of the production method influences the maximum panel size and hence optimal number of panels. The selection of fixing method influences the optimization process. The properties of the concrete mix used for different production methods influences the optimization process.	Development of a software plug-in embedded with manufacturing limits, associated fixing methods and material properties in a common software language.
C	The demands for edge-returns and panel offsets determines the best production method. The surface quality demands determine the most appropriate production method. The required curvature of the mould is limited by the production method selected. The production method and conditions influences the curing time and speed of manufacture.	Development of a novel optimally linked manufacturing process for complex geometry GFRC panels.
D	The current modes of transportation to site limit maximum panel dimensions and places limits at the optimization stage. The maximum panel dimension/weight of panels that can be man-handled/installed transportation places limits at the optimization stage. The panel dimension/weight influences installation speed and places limits at the optimization stage. The buildability of the design solutions places limits at the optimization stage.	Development of a software plug-in with optimal transportation, handling and installation details in a common software language.

TABLE 5.1 Barriers and proposed solutions for a fully automated and digital process.

The barriers may be overcome by integrating plug-in tools into conventional 3D CAD software, with embedded limitations that reduce or minimize the delays caused by each feedback loop. The 3D CAD software must be sufficiently adaptable to all the stages of the novel process and the plug-ins must allow an architectural form to be generated that resolves the limitations at each stage of the design and manufacturing process.

§ 5.5.1 Plug-in A. Embedded panel optimization.

Optimization of the surfaces to rationalise the numbers of unique panels to a minimum would be performed automatically by this plug-in, thereby reducing or eliminating the number of iterations in design feedback loop A. This plug-in would also inform the cost of producing the geometry and if necessary revert to a facetted geometry. Current developments in computational geometry allow surfaces to be rationalised to facetted solutions, however there are still limitations when a complex shape must be transformed into a facetted surface with planar quads, that results in significant changes in the original free-form architectural intent (11).

§ 5.5.2 Plug-in B. Embedded manufacturing limits, fixing methods and material properties

Once the GFRC elements have been rationalised, while still retaining the architectural intent, it is possible to digitize each element for production, however, once the production stage commences the whole process remains vulnerable if design changes are requested. This plug-in would allow a full digital file of each individual GFRC element to be generated, including edge-returns and panel offsets (2), with the known current fabrication limitations built into the file meta-data. The digital file would also have to incorporate information such as the overall dimensions, the height of the edge-return, and thickness of the panel. This complete description of the complex geometric shape of the GRFC panel would have to be defined by a 3D CAD drawing or similar digital file required for automated and digital production. Such a fully digital "virtual" design environment would allow the effects of design changes at this stage to be assessed before the production commences and reduce the delays caused by such changes during loop B.

§ 5.5.3 Plug-in C. Optimization a complex geometry GFRC manufacturing process to allow automation.

To allow a fully automated production process it is necessary to develop a plug-in that can utilize the digital input file generated by plug-in B. Plug-in C would analyse the overall panelization of the geometry and determine the number of moulds necessary for the entire building envelope. This plug-in would also determine the most effective production sequence and allow the same mould to be used during sequential production days if required.

§ 5.5.4 Plug-in D. Optimized transportation, handling and installation details.

This plug-in will allow the production and the panelization to be optimised in accordance with both the installation sequence needed on site and the fastest production speed and packing of the elements for transportation. However for complex geometry buildings with little repetition the installation sequence governs the installation speed. This plug-in should define the most optimal production sequence to allow a fast installation speed, however, this means that repetition of mould usage is low and the logistics of making re-useable moulds need to be considered. Alternatively the plug-in could optimize the production in terms of the fastest production speed where the moulds are reused as many times as needed over several casting days. This would require the panels to be stored until they were needed in the installation sequence. The second production method needs greater initial production time, but is more cost efficient and has a shorter overall programme.

§ 5.6 Development of a new mould system

Generating the mould is key to advancing towards a fully automated and digital process for complex geometry GFRC. Existing mould systems are not sufficiently flexible to meet the demands of today's requirements therefore a new method to produce the mould must be developed (23) (19). The method described in (19) only addresses the mould systems using premixed thin-walled GFRC, therefore a variation has been developed that allows the production of complex geometry thin-walled GFRC using the sprayed method while simultaneously allowing an edge-return.

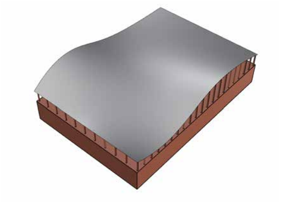


FIGURE 5.6 Positioning of flexible table.

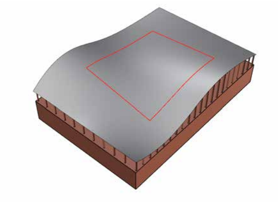


FIGURE 5.7 Outlining the boundaries of the panel on the flexible table.

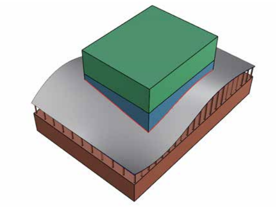


FIGURE 5.8 Casting the foam mould on the flexible table.

The production of the new mould system for complex geometry sprayed thin-walled GFRC is shown in Figures 5.6 – 5.8 and described as follows:

– Figure 5.6: Positioning of the surface of the flexible table in the correct geometric form, using a predefined shape developed in, and informed by, the 3D software.
– Figure 5.7: Projecting the boundaries of the element onto the flexible mould.
– Figure 5.8: Casting the mould on the flexible table and curing of the foam, (shown in blue).

The production of the new mould is the first stage of the production process for complex geometry GFRC. This method will enable unique complex geometry shaped foam to be cast with the possibility of an edge-return that can be used as moulds for GFRC panels. The method enables a faster mould production method for GFRC than the current CNC milling solution and enables the re-use of the flexible table to produce many foam moulds.

While the foam mould replicates the surface generated on the flexible table, it does not allow for an edge-return if a GFRC panel was cast directly onto it. In principle it would be possible to use a silicone band to mark the boundary of the panel but when the fibre concrete mix is sprayed this would only allow for a panel with a constant thickness and not permit an edge-return that protrudes from the back surface of the GFRC panel. The finished foam mould is shown in Figure 5.9.

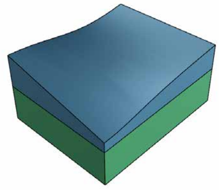


FIGURE 5.9 Finished mould.

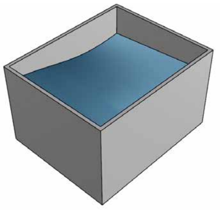


FIGURE 5.10 Side walls are added to the foam mould.

The next stage of the process towards an automated manufacturing process is the following;

– Figure 5.9. Removing the foam mould from the flexible table and turning it upside down.
– Figure 5.10: Add side walls to the foam mould to enable an edge-return to be cast.

The remaining process is the casting of the GFRC element. To control the thickness and enable an edge-return it is necessary to use the sprayed method to produce the GFRC panels.

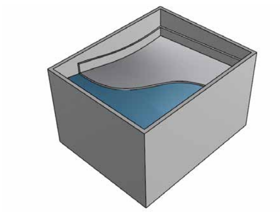


FIGURE 5.11 Sprayed concrete matrix is cast in the mould system.

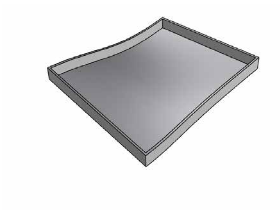


FIGURE 5.12 Curing of the GFRC panel.

FIGURE 5.13 Finished free-form GFRC panel with an edge-return.

The method for casting thin-walled GFRC panels as part of a novel fully automated and digital manufacturing process is described as;

- Spraying the panel in the mould, (figure 5.11)
- Spraying the 2mm face coat, to achieve a high quality finish.
- Spraying the first fibre mix
- Positioning the first free-form fibre mesh
- Spraying the second fibre mix
- Positioning the second free-form fibre mesh
- Spraying the last fibre mix (back coat)
- Initial cure (24h) and demoulding (Figure 5.12)
- Final 28-day cure of the GFRC (Figure 5.13)

The new mould system allows the concrete to cure for 28 days on a more cost effective foam mould, rather than leaving it on the flexible table to cure. This leaves the flexible table free to be used to produce further moulds rather than remaining unused during the 28 day curing process.

The process for producing the new foam mould has been patented (23) and contributes significantly to the development of a novel fully automated and digital design and manufacturing process for complex geometry thin-walled GFRC. This would allow the production of panels at a lower cost combined with increased production speed and higher finished surface quality.

This new moulding process has been tested and a prototype of a mould has been produced, as shown in figures 5.14-5.16.

FIGURE 5.14 Generating the shape

FIGURE 5.15 Casting the foam mould on the shape

FIGURE 5.16 Completed mould & finished surface

Figures 5.14 - 5.16 show the 3 primary production stages. This new moulding system resolves the current time consuming and costly production of moulds for thin-walled GFRC panels and reduces the delays caused by feedback loop C

The limitation of the resulting foam mould is that it is restricted to the size of the flexible table and that the edge-return must be projected from the surface. The next steps will be to test the mould with the GFRC cast on the mould. Additional research must to be done to develop the mould system to allow for edge-returns that are normal to the surface and potentially edge-returns with variable angles to the surface of the panel.

§ 5.7 The environmental impact of mould materials

Rationalization of the panels will identify the degree of panel repetition, enabling any moulds required for such re-use to be stored if the same geometry is ever required again. When exploring the re-use potential of the new mould system (19) it was evident that the environmental impact of the polyurethane foam solution was poor compared to other materials because they could not be re-formed into fresh moulds and they had a high embodied energy compared to wax or sand. All the materials suitable for casting GFRC moulds into complex shapes are shown in table 5.2, including thermo plastic, Wax[7] (24) and moulding sand.

7 Wax has been used in lost-wax casting and investment castings as a standard product.

MOULD MATERIAL	COST	FABRICATION TIME	DENSITY (KG/M³)	CASTING CYCLES	REUSABILITY	LABOUR INTENSITY	EMBODIED ENERGY MJ/ KG (25)
Low density foam (LDPU)	Low	Low	15-16	10 x	Low	Low	101.5
High density foam (HDPU)	Low	Low	37-38	20 x	Low	Low	
Thermo plastic	Medium	Medium	980	100 x	Medium	Low	109.2
Wax	High	High	900-980	1 x	High	High	52
Moulding sand	Medium	Medium	2590	1 x	Medium	Medium	0.08

TABLE 5.2 Evaluation of alternative material for the new mould system.

Based on the environmental impact alone, wax would be the preferred solution, but it is difficult to integrate into a fully digital manufacturing process due to problems with concrete residue in the re-melted wax. The main drivers for combining high and low density foam were; the low fabrication cost, the high fabrication speed and the low weight of the mould after it has been cast. The advantage of using the mix of LDPU and HDPU was that the surface could be reused for more castings and the weight of the mould was minimal. Despite this, research into more environmentally benign solutions should continue.

§ 5.8 Impact on the building industry

The new mould for this novel manufacturing process for complex geometry thin-walled GFRC will benefit all the relevant stakeholders because progress between each stage of the design and manufacturing processes is dis-jointed. The proposed process would be novel because it is a continuous process that eliminates the main bottlenecks, the manufacture of the moulds and feedback loops, while also reducing the total number of stages to only 4 by eliminating the choice of production method. The impact of each stage is shown in Table 5.3.

DESIGN STAGE	ADVANCES TO CURRENT PRACTICE	STAKEHOLDERS	IMPACTS/BENEFITS
Initial design	Design development of the architectural form with the embedded knowledge from the detailed design and the production and installation through a software plug-in, and a common software language at all the 4 stages.	Architects and Engineering Consultants	Optimised and continuous design development
Detailed design	The detailed design would be possible without having to adapt the architectural form developed in the initial design for panelization, and the design development would allow information from the production and installation to be incorporated into the detailed design stage by software plug-ins, and a common software language at all the 4 stages.	Architects Engineering Consultants Envelope Contractors	Optimised and continuous design development
Production	The fully automated and digital manufacturing method would be adapted to the initial design and detailed design stages of the novel process, allowing the complex geometry panels to be manufactured in accordance with the initial architectural intent, avoiding costly redesigns due to value engineering, and the architectural form being adapted to a restricted production method.	Manufacturers	Optimised production Reduced production cost and production time
Installation	The installation would benefit from the novel process because it allows the handling and transportation limitations of the GFRC panels to be embedded into the initial design and detailed design stages, thus avoiding redesign and production of panels at the installation stage because the initial architectural geometry is not buildable.	Building Envelope Contractors	Optimised installation Reduced installation cost and installation time

TABLE 5.3 Impact of novel manufacturing process on all relevant stakeholders.

The overall impact for the industry would be greater utilization of complex geometry thin-walled GFRC in building envelopes, at significantly reduced cost compared to current free-form thin-walled GFRC panel manufacturing processes.

§ 5.9 Further research

To progress the novel process it would be necessary to fully develop and test the plug-in tools with all the embedded limitations highlighted in Figure 5.1. and Table 5.2. These plug-ins would allow architectural forms to be generated where the feasibility of the manufacture and the cost associated is a known parameter. Further steps are necessary to develop a production line that incorporates the software plug-ins with 1 common software "language" between the different stages, to create moulds as shown in Figures 5.6 – Figure 5.10. This will allow shapes to be cast with a complex geometry glass fibre mesh adapted to each unique shape. Finally, more sustainable moulds, with lower environmental impact should be sought to replace the proposed non-recyclable foam moulds.

§ 5.10 Conclusion

In this chapter a new mould for a novel fully digital and automated manufacturing process is proposed and the impact it will have on the industry is described. The current limitations that restrict the manufacture of complex geometry GFRC panels during the five-stage processes are highlighted and it is shown how feedback loops between each stage lead to the redesign or remanufacture of cast panels, prolonging the process and increase the cost of realising envelopes with complex geometry GFRC. The novel process proposed would reduce this to only 4 stages, eliminating the stage normally required to select the most appropriate production method. Plug-in solutions to these feedback loops have been characterized to fully realise an automatic and digital process. The plug-in software would embed all limitations from the fabrication process into conventional 3D CAD software to allow the architectural form and the panel optimization to be a contiguous part of the manufacturing process. The new approach to making moulds and casting the GFRC panels, combined with the plug-ins enables a novel fully digital and automatic process for the manufacture of complex geometry GFRC panels to be realised. The field of complex geometry thin-walled GFRC is in it's development stages, so limited research has been conducted in this field. The research done by H.R. Schripper (3) describes the development to date and evaluated the use of flexible tables and proposed a solution to advance the process of the manufacturing of thin-walled concrete, however, it did not explain in detail the process necessary to advance complex geometry thin-walled GFRC. The presented work outlines a process that will advance existing developments in this field for a thin-walled GFRC manufacturing process at a lower cost that enables more complex geometry buildings to be realised. Further research will develop the plug-ins to manufacture, and test prototype complex geometry thin-walled GFRC panels as part of a fully automated production line.

§ 5.11 References

1 *Advances in the Application of Thin-Walled Glass Fiber Reinforced Concrete Elements.* **Henriksen, T., Lo, S. and Knaack, U.** 1, s.l. : ASTM International, 19 May 2015, Advances in Civil Engineering Materials, Vol. 4, p. 17.

2 *An innovative approach to manufacture thin-walled glass fibre reinforced concrete for tomorrow's architectural buildings envelopes with complex geometries.* **Henriksen, T., Lo, S. and Knaack, U.** September 2015, Journal of Building Engineering.

3 **Schripper, H.R.** *Double-curved precast concrete elements, Research into technical viability of the flexible mould method.* Delft : TUDelft, 2015.

4 **ACI 544.1R.** *State-of-the-Art Report on Fiber Reinforced Concrete.* s.l. : ACI, 1996.

5 **ACI 549.2R.** *Report on Thin Reinforced Cementitious Products.* s.l. : ACI, 2004.

6 **Fordyce, M. W. and Wodehouse, R. G.** *GRC and Buildings.* Norfolk : Butterworth & Co Ltd, 1983.

7 **Brameshuber, W.** *Textile Reinforced Concrete - State of the Art Report of Rilem TC 201 - TRC.* s.l. : Rilem Publications SARL, 2006.

8 **Bentur, A and Mindess, S.** *Fibre Reinforced Cementitious Composites, 2nd Edition.* NY : Taylor & Francis, 2007.

9 **Mobasher, Barzin.** *Mechanics of Fiber and Textile Reinforced Cement Composites.* s.l. : CRC Press, 2012.

10 *Ruled Surfaces for Rationalization and Design in Architecture.* **Floery, S. and Pottmann, H.** New York City, October 21-24, 2010 : s.n., 2010. ACADIA. pp. 103-109.

11 *Architectural Geometry.* **Pottmann, H., et al., et al.** 29 December 2014, Computers & Graphics (Preprint).

12 **Agoston, M. K.** *Computer Graphics and Geometric Modelling.* London : Springer, 2005. pp. Pp 638-645. ISBN 978-85233-818-3.

13 **Jones, Glyn.** *Practical design guide for glass reinforced concrete.* s.l. : GRCA, 2005.

14 **PCI.** *MNL-128-01 "Recommended pratice for glass fiber reinforced concrete panels".* Fourth. s.l. : PCI, 2001.

15 **H. Pottmann, A. Asperl, M. Hofer, A. Kilian.** *Architectual Geometry.* s.l. : Bentley Institute Press, 2007.

16 *Interview: Intention of architectural appearance of GFRC facades, related to the Kapsarc project in Saudi Arabia.* **Bishop, E.** 2014.

17 *A UHPFRC Cladding Challenge: The Fondation Louis Vuitton Pour La retion "Icebreg".* **Aubry, S., et al., et al.** marseille : RILEM, 2013. RILEM-fib-AFGC Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete.

18 *Interview with Wolfgang Rieder regarding production of premixed GFRC.* **Rieder, Wolfgang.** 2013.

19 *A new method to advance complex geometry thin-walled glass fibre.* **Henriksen, T., Lo, S. and Knaack, U.** 2016, Journal of Building Engineering (Under review).

20 *Design and Fabrication of Topologically Optimized Structures; An Integral Approach.* **Feringa, Jelle and Søndergaard, Asbjørn.** Prague : s.n., 2012. eCAADe 30, Modes of Production.

21 *Dynamic Double-Curved Mould System.* **Raun, C.** Berlin : s.n., 2011. Design Modelling Symposium.

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

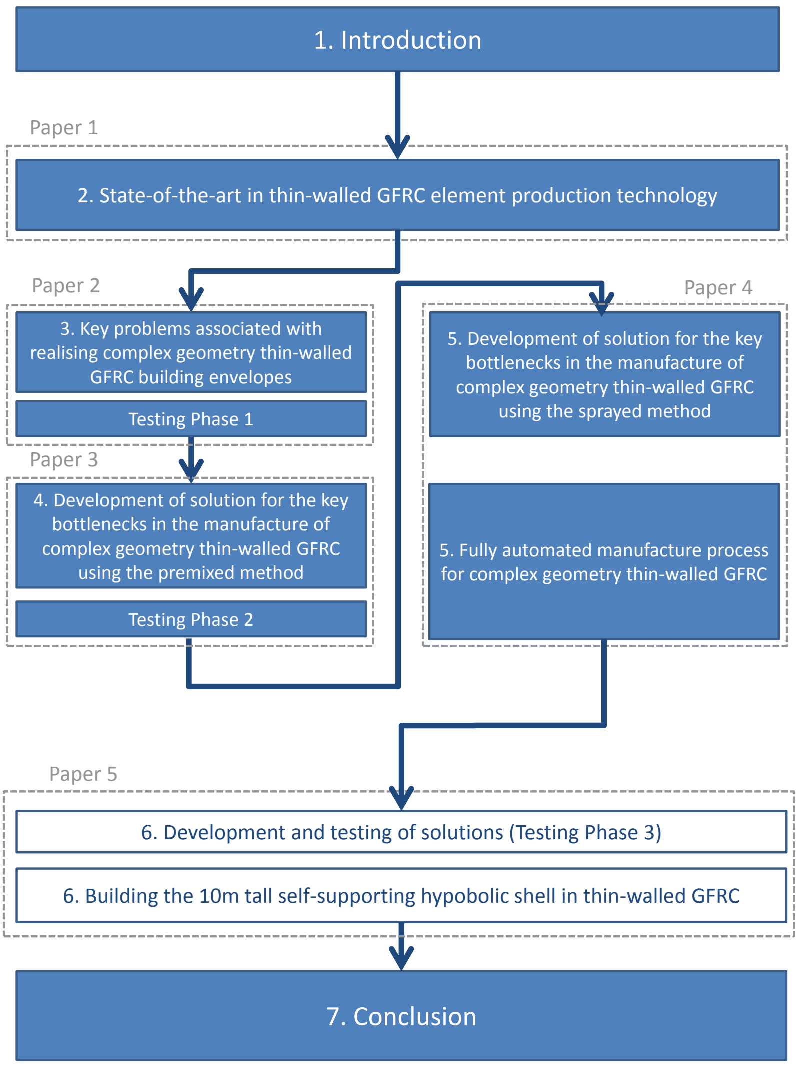
23 *Patent: Method for producing a planar element with a surface deviating from a flat surface, moulding part for producing such a planar element, and planar element.* **Henriksen, T. and Raun, C.** 2013.

24 **Gramazio, F. and Kohler, M.** TailorCrete, 2009-2013. [Online] 2011 **йил**. http://dfab.arch.ethz.ch/web/d/forschung/164.html.

25 **Hammond, G. and Jones, C.** *Inventory of Carbon and Energy.* Version 2.0. s.l. : ICE, 2011.

26 *FRC in Complex Geometry Facades.* **Henriksen, T. and Schiftner, A.** Guimaraes : RILEM International S.A.R.L., 2012. 8th Rilem international Symposium on Fibre Reinforced Concrete. pp. 73-74.

131 Developing a solution for the sprayed concrete method and proposing automated process.


1. Introduction
Paper 1
2. State-of-the-art in thin-walled GFRC element production technology
Paper 2
3. Key problems associated with realising complex geometry thin-walled GFRC building envelopes
Testing Phase 1
Paper 3
4. Development of solution for the key bottlenecks in the manufacture of complex geometry thin-walled GFRC using the premixed method
Testing Phase 2
Paper 4
5. Development of solution for the key bottlenecks in the manufacture of complex geometry thin-walled GFRC using the sprayed method
5. Fully automated manufacture process for complex geometry thin-walled GFRC
Paper 5
6. Development and testing of solutions (Testing Phase 3)
6. Building the 10m tall self-supporting hypobolic shell in thin-walled GFRC
7. Conclusion