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Thomas Henriksen

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Summary

Thin-walled glass fibre reinforced concrete (GFRC) panels are being used as the primary cladding material on many landmark buildings especially in the last decade. GFRC is an ideal material for building envelopes because it is durable, it can resist fire and the environmental impact is low compared to other materials, because the base materials used in the production of GFRC are widely available throughout the world. Thin-walled GFRC was initially developed as a cladding material in the 1970s and 1980s where the majority of the available research lies.

The introduction of 3D CAD software has enabled the design of buildings with complex shapes that, in the past, would have been rationalised to meet budget and time constraints. However, when GFRC has been proposed for buildings with a complex free-form geometry it has been replaced with alternative materials such as glass reinforced plastic (GFRP) due to the high cost and time required to fabricate suitable GFRC panels using conventional manufacturing methods. The literature showed that empirical performance characterization of GFRC had not been researched in detail regarding the limits of functionality or any systematic approach to understanding their use in complex geometry building envelopes.

As a first step the key architectural demands, the main barriers and limitations in the manufacture of complex geometry thin-walled GFRC were identified by interviewing and visiting manufacturers, designers and key buildings. This identified the key barrier to be the process of producing the mould for casting the complex geometry GFRC panels. Solutions to resolve them were tested over several stages for each of the main production methods most suited for the manufacture of thin-walled GFRC, namely; the automated premixed method, the premixed method and the sprayed method. The results from the laboratory testing over all the stages, and the prototype structure manufactured with the identified solution from the testing, answered the main research question:

How can the manufacture of complex geometry thin-walled GFRC be advanced to meet today's architectural demands?

So, the architectural demands for thin-walled GFRC cladding were identified, together with a clearly defined range of complexity of thin-walled GFRC panels. The key demands were; a smooth surface texture, no visual fibres in the surface, minimal air-bubbles or voids, consistent colour across all thin-walled GRFC elements, no visible cracks, and the need for edge-returns and panel offsets. The suitability of selected production methods were evaluated against these demands. Firstly the automated

premixed method was tested on a flexible table, (single reconfigurable mould surface, with computer controlled actuators capable of forming free-formed geometries). This showed that the flexible table alone would not meet the requirements for an edge-return, with the manufacturing speed required, to produce many unique shaped panels within normal building project time-schedules. Following this test a solution was proposed that used the flexible table to produce free-formed shaped moulds using fast curing foam, enabling moulds to be produced within hours allowing more rapid utilization of the flexible table.

This solution was first tested for the premixed method by casting positive and negative mould parts enabling an edge-return to be cast because flexible tables are only able to produce moulds with a continuous surface. The new mould solution for complex geometry shapes also demonstrated that it was difficult to avoid air-bubbles and voids when casting the GFRC panels using the premixed method. So a second mould solution was developed for the sprayed method. This resolved the challenges of forming an edge-barrier on the mould, while allowing an edge-return to be successfully cast on a double curved panel that met the key architectural demands.

From the research and the tests it was possible to devise a fully automated process for the manufacture of complex geometry thin-walled GFRC, comprised of:

- Stage 1: Initial architectural geometric concept.
- Stage 2: Panelization and geometric offsetting.
- Stage 3: Identifying the right production method.
- Stage 4: Casting process.
- Stage 5: Transportation and Installation.

Solutions for each of these stages all contributed to advances that will enable current and future free-form thin-walled GFRC architectural designs to be realised.

The contribution to knowledge from the tests and the resulting automated process was used to produce the moulds for 9 unique double curved elements to form each row of a 10m tall self-supporting thin-walled shell. This show-cased how the identified solution enabled a faster and more cost effective method to produce free-form thin-walled GFRC panels. One of the main conclusions of the research showed that the sprayed method currently provides most flexibility in the manufacture of complex geometry thin-walled GFRC panels when the identified architectural demands must be met. To advance the manufacture of complex geometry thin-walled panels further a fully automated and digital manufacturing process must be developed. As identified in the research this can be done by upgrading current automated premixed production lines by integrating the new solution for complex geometry shaped moulds into the production line and automatically spaying the GFRC onto the mould.

When fully developed this fully automated method would enable free-form shell elements to be produced, that may also incorporate insulation, allowing segments for a self-supporting free-form shell to be constructed.

With this research the current architectural knowledge base has been advanced in terms of complex geometry thin-walled GFRC for building envelopes. The identified solutions should allow building with complex geometries to be realised using thin-walled GFRC as the envelope cladding.

Samenvatting

Dunwandige panelen gemaakt van glasvezel versterkt beton (GFRC) worden gebruikt als primair bekledingsmateriaal van veel landmarks uit met name het laatste decennium. GFRC is een ideaal materiaal als gebouwomhulling omdat het duurzaam is, vuurbestendig is en het een lage milieubelasting heeft in vergelijking met andere materialen, omdat de grondstoffen die gebruikt worden voor de productie van GFRC wereldwijd beschikbaar zijn. Dunwandige GFRC is oorspronkelijk ontwikkeld als een bekledingsmateriaal in de jaren 70 en 80 waarin ook de meerderheid van het beschikbare onderzoek is gedaan.

De introductie van 3D CAD software heeft het mogelijk gemaakt om gebouwen te ontwerpen met complexe vormen die in het verleden gerationaliseerd zouden moeten worden om binnen het budget en de tijdsplanning te blijven. Echter, toen GFRC werd voorgesteld voor gebouwen met een complexe free-form geometrie werd het vervangen door alternatieve materialen zoals glas versterkt plastic (GFRP) vanwege de hoge kosten en de tijd die nodig was om een geschikt GFRC paneel te fabriceren met de gebruikelijke fabricagemethoden. Uit de literatuur is gebleken dat de empirische prestatie-eigenschappen niet in detail zijn onderzocht met betrekking tot de grenzen van de functionaliteit of andere systematische aanpak om het gebruik ervan als complexe geometrische gebouwomhulling te begrijpen.

Als eerste stap binnen het voorliggende onderzoek zijn de belangrijkste architectonische eisen, de belemmeringen en de beperkingen van de fabricage van complexe geometrische dunwandige GFRC geïdentificeerd door het interviewen van fabrikanten en ontwerpers en het bezoeken van belangrijke gebouwen. Hieruit bleek dat het grootste obstakel het proces van het produceren van de mal voor het gieten van de complexe geometrische GFRC panelen was. Oplossingen hiervoor werden getest in verschillende fasen van elk van de productiemethoden die geschikt waren voor de fabricage van dunwandige GFRC, namelijk: de geautomatiseerde voor-gemixte methode, de voor-gemixte methode en de spuit- methode. De resultaten van de laboratoriumtests van alle stadia en de prototypes die geproduceerd waren op basis van de geïdentificeerde oplossing uit de tests, beantwoorden de belangrijkste onderzoeksvraag:

Hoe kan de fabricage van complexe geometrische dunwandige GFRC worden verbeterd om aan de huidige architectonische eisen te voldoen?

De architectonische eisen voor de dunwandige GFRC bekleding zijn vastgesteld, samen met een duidelijk beschreven range van complexiteit in de dunwandige GFRC panelen. De belangrijkste eisen waren een gladde structuur, geen zichtbare vezels aan het oppervlak, minimale luchtbellen of holle ruimtes, een consistente kleur bij alle dunwandige GRFC panelen, geen zichtbare scheuren en de mogelijkheden voor voor edge-returns en paneel offsetting. De geschiktheid van de geselecteerde productiemethodes zijn geëvalueerd aan de hand van deze eisen. Als eerste is de geautomatiseerde voor-gemixte methode getest op een flexibele tafel (een computer gestuurde pneumatische tafel die in staat is om free-form panelen te maken). Hieruit bleek dat de flexibele tafel alleen niet aan de eisen voldeed voor edge-return met de nodige productiesnelheid, om veel uniek gevormde panelen te produceren binnen de normale bouwproject tijdschema's. Naar aanleiding van deze test is een oplossing voorgesteld waarbij de flexibele tafel gebruikt werd om free-form mallen te maken gebruikmakend van sneldrogend schuim, waarbij het mogelijk is mallen te produceren binnen een paar uur zodat sneller gebruik van de flexibele tafel mogelijk is.

Deze oplossing werd voor het eerst getest op de voorgemengde methode door het gieten van positieve- en negatieve mal-onderdelen waardoor een edge-return mogelijk is, omdat de flexibele tafels alleen in staat zijn om mallen te produceren met een doorlopend oppervlak. De nieuwe mal-oplossing voor complexe geometrievormen toonde ook aan dat het moeilijk was om luchtbellen en holle ruimten te vermijden bij het gieten van de GFRC panelen met behulp van de voorgemengde methode. Daarom is er een tweede mal-oplossing ontwikkeld voor de gespoten methode. Dit loste de uitdagingen bij het vormen van een edge-barrière op de mal op, terwijl het mogelijk werd gemaakt om succesvol een edge-return te gieten op een dubbel gekromd paneel dat voldeed aan de belangrijkste architectonische eisen.

Uit het onderzoek en de tests bleek het mogelijk te zijn om een volledig geautomatiseerd proces te ontwikkelen voor de vervaardiging van complexe geometrische dunwandige GFRC, bestaande uit:

- Fase 1: Initiële architectonische geometrische concept.
- Fase 2: Panelization en geometrische offsetting
- Fase 3: Het identificeren van de juiste productiemethode.
- Fase 4: Gietproces.
- Fase 5: Transport en Installatie.

Oplossingen voor elk van deze fasen hebben bijgedragen aan de voortgang van de realisatie van de huidige en toekomstige free-form dunwandige GFRC in architectuurontwerpen.

De bijdrage aan de kennis van de tests en het resulterende geautomatiseerde proces zijn gebruikt om de mallen te maken voor 9 unieke dubbelgekromde elementen om elke rij van een 10 meter hoog zelfdragende dunwandige toren te vormen. Dit liet zien hoe de geïdentificeerde oplossing een snellere en meer kosteneffectieve methode is om free-form dunwandige GFRC panelen te produceren.

Uit een van de belangrijkste conclusies van het onderzoek bleek dat de gespoten methode op dit moment de meeste flexibiliteit bij de vervaardiging van complexe geometrie dunwandige GFRC panelen voorziet, wanneer aan de architectonische gestelde eisen architecturale moet worden voldaan. Om de vervaardiging van dunwandige GFRC panelen met een complexe geometrie verder te ontwikkelen, moet een volledig geautomatiseerd en digitaal productieproces worden ontwikkeld. Zoals aangegeven in het voorliggende onderzoek kan dit worden gedaan door het verbeteren van bestaande geautomatiseerde voorgemengde productielijnen, door integratie van de nieuwe oplossing voor complex gevormde mallen in de productielijn en automatisch de GFRC op de mal te spuiten.

Als deze volledig geautomatiseerde methode volledig is ontwikkeld wordt het mogelijk free-form gebouwschillen te produceren, die eventueel ook isolatie bevatten, die het mogelijk maakt segmenten van een zelfdragende free-form gebouwschil te construeren.

Met dit onderzoek is de huidige beschikbare bouwkundige kennis vergroot op het gebied van complexe geometrie dunwandige GFRC in de gebouwomhulling. De geïdentificeerde oplossingen moeten het mogelijk maken een gebouw met complexe geometrie te realiseren met behulp van dunwandige GFRC als gebouwomhulling.

1 Introduction

"Everything in nature, whatever you find is an organic shape, is double curvature, nothing plane." Heinz Isler, August 1999

§ 1.1 General introduction

Glass Fibre Reinforced Concrete (GFRC) as a material has been developed over the last 50 years into the material it is today, using glass fibres for reinforcement, (1) (2) (3) (4). Since the development of GFRC, it has mostly been used as a cladding material for buildings as thin-wall GFRC panels. However, the history of thin-walled panels (reinforced with asbestos fibres) can be traced back to 1901, where Ludwig Hatschek (5) developed the method known today as the Hatschek Method (6). The product is better known as "*Eternit*". However, the production method used asbestos fibres for reinforcement and due to their related health and safety issues (7), alternative fibre materials were sought such as glass fibres used in the yacht-building industry and were a suitable substitute. Thin-walled GFRC was very popular during the early days of its development and landmark buildings, such as the 30 Cannon Street building London, (formally Credit Lyonnais), by Whinney, Son & Austen Hall in 1974-7 (8), and the UOP Fragrance Factory in Tadworth UK, by Rogers and Piano in 1973-4 (9), were clad with this material. Thin-walled GFRC cladding in the 1980s and 1990 was being used predominately as decorative cladding (10), however, for the 2008 Expo in Zaragoza, Zaha Hadid Architects (ZHA) used thin-walled GFRC as cladding on the Expo bridge and for the 2010 world cup in South Africa, HOK architects designed the Soccer City stadium with thin-walled GFRC (11). Both projects utilized flat thin-walled GFRC panels, shown in Figure 1.1 and Figure 1.2.

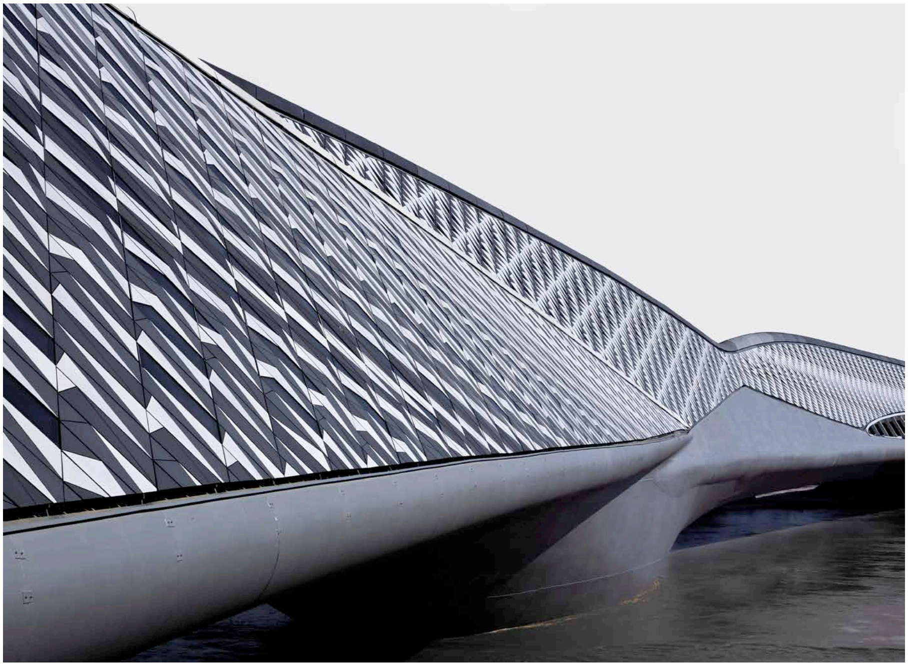

FIGURE 1.1 Expo Bridge in Zaragoza, ZHA Architects (Photo Rieder GmbH)

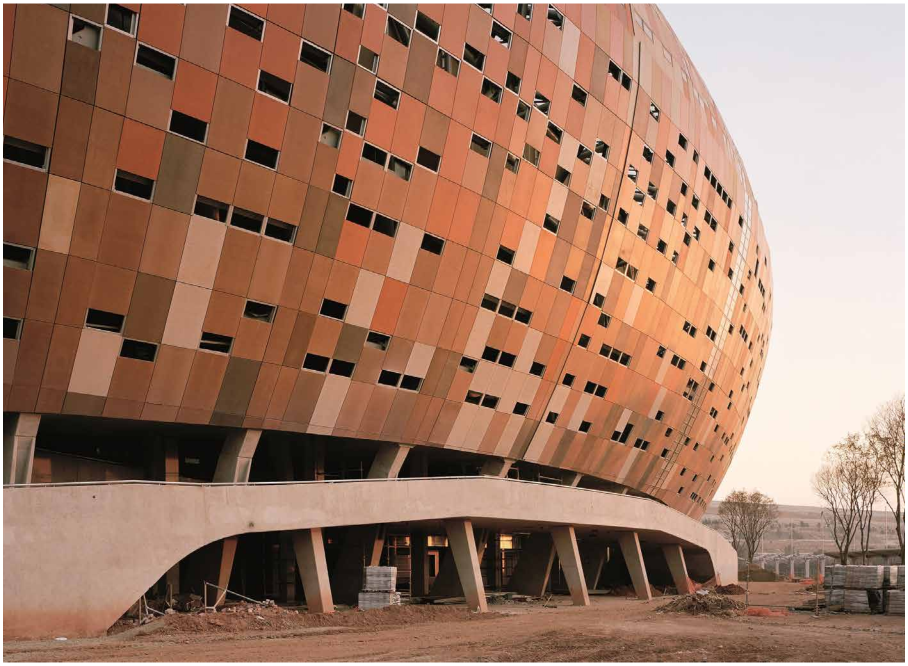

FIGURE 1.2 Soccer City stadium, HOK Architects (Photo Rieder GmbH)

One of the first projects to propose complex geometry thin-walled GFRC was the Heydar Aliyev Center in Baku (12) designed by ZHA. During the construction of the project the cladding material of the building was changed to glass fibre reinforced concrete due to the high cost and complexity of manufacturing the many unique panels. The 2016 KAPSARC project in KSA design by ZHA utilizing flat GFRC, with edge-returns and panel offsets to achieve a monolithic appearance for the building envelope (13), the project was delayed because the initial manufacturing method (premixed GFRC) chosen to fabricate the panels failed to meet the aesthetic requirements of the project, Mock-up is shown in Figure 1.3.

FIGURE 1.3 Mock-up Kapsarc, ZHA Architects

To successfully realise complex geometry building envelopes using thin-walled GFRC then the production method for the GFRC panels plays a key role. The main method of production for thin-walled GFRC panels is the sprayed concrete method. This method allows the simple production of decorative elements with minimal flaws in the surface. The main alternative production method is the premixed method. The premixed method is often used for flat panels but is, in general, not suited for the production of complex geometry panels. The application of the GFRC as a free-form material still has limitations due to the cost of producing complex geometries in GFRC. The production cost is directly linked to the level of geometric complexity and greater complexity is incurred if panels have a variable thickness, e.g. if they possess elements such as edge-returns. Edge-returns are required when the panels are joined and are important from a visual point of view to give an overall monolithic appearance (13).

For complex geometry panels there are currently no cost effective solutions that meet the production quality requirements specified by lead designers. At the same time GFRC has not been researched in detail regarding the empirical performance characterization limits of functionality/systematic approach to understanding their use in complex geometry building envelopes. This study identifies the limitations of current production methods and recommends new solutions and methods to enable complex geometry thin-walled GFRC building envelopes to be technically and economically viable while meeting the architectural demands and project time constraints.

§ 1.2 Terminology

Fibre reinforced concrete.

Fibre reinforced concrete encompasses all the different fibres that may be mixed with concrete, including glass, synthetic, organic, and metal fibres, (6). This thesis predominantly focuses on glass fibre reinforced concrete, as it is the fibre preferred by the industry for use with the sprayed method. Irrespective of which fibre is used, many variations in the concrete mix exist. This research considers two main types, ordinary Portland cement (OPC) based concrete, and ultra high performance concrete (UHPC), because these are the most commonly used in production of thin-walled GFRC. Ordinary Portland cement is a low strength concrete generally used for GFRC especially for the sprayed method, whereas ultra high performance concrete is used especially for long spanning elements where higher strength concrete is required, but predominantly for the premixed method, because of the low viscosity of the UHPC mix.

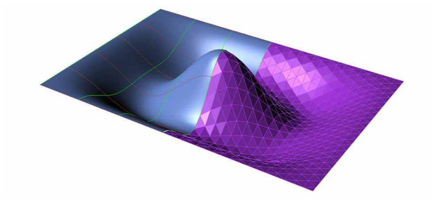

FIGURE 1.4 Tessellated free-form

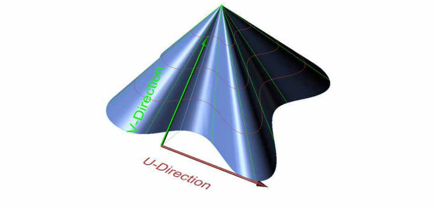

FIGURE 1.5 Single curvature

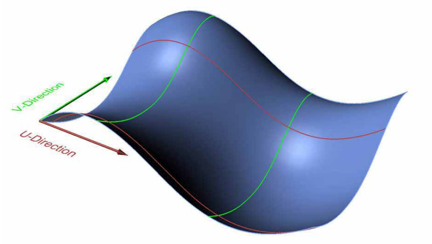

FIGURE 1.6 Double curvature

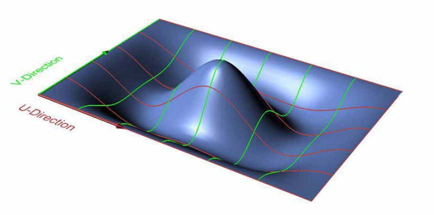

FIGURE 1.7 Free-form

Complex geometry

The term complex geometry is used to describe the different types of geometries that form building envelopes. The term is used for geometries ranging from tessellated shapes that are reconfigured into a complex form, as can be seen in Figure 1.4, to geometries based on single curvatures, Figure 1.5, double curvatures, Figure 1.6, to true free-form geometries, Figure 1.7, with little or no repetition of the pattern resulting in panelization of many unique panels.

Thin-walled elements

In this research thin-walled elements are defined as concrete elements with a thickness of less than 60mm, (disregarding any edge-returns or local reinforcement ribs). Thin-walled elements do not have any conventional reinforcement so the fibres provide the only reinforcement in the panels. If GFRC elements have an edge-return or an offset, (required for openings), projecting from the primary surface in addition to a complex geometry, then the manufacture of the GFRC element is even more complex. The edge-return is defined as an up-stand from the edge of the panel, as shown in Figure 1.8 and the panel offset is shown in Figure 1.9.

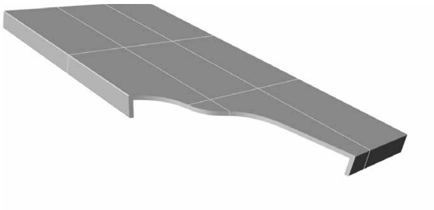

FIGURE 1.8 Flat panel with an edge-return

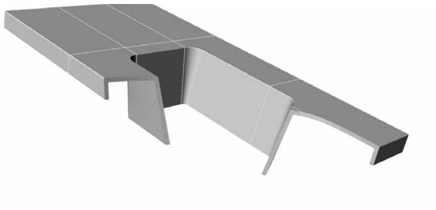

FIGURE 1.9 Flat panel with an edge-return and a panel offset

§ 1.3 Background information

Production methods for thin-walled GFRC

Three main production methods are considered in this research;

- The premixed method is similar to that used for conventional concrete but with fibres added to the mix before the concrete is poured into a mould. To avoid fibres breaking and clustering the fibres are limited in size and kept to a low content ratio. The premixed method allows the use of ultra high performance concrete.
- The sprayed method uses a spray gun to apply the concrete mix onto the moulds. The fibres are added to the mix in the spray gun to give better control of the fibre orientation and allow a higher fibre content and longer fibres.
- The automated premixed method originates from the Hatchek method, (5), and uses premixed concrete with the fibres mixed into the concrete. The state-of-the-art automated premixed methods allow fibre meshes to be integrated into the panels.

§ 1.4 Problem statement

Thin-walled GFRC is becoming the material of choice for key landmark buildings throughout the world. Its durability, fire resistance, the ability to incorporate different colours into the concrete mix while being cast with different surface textures and complex shapes makes it perfect for building cladding of such landmark buildings, that often have complex geometries. The material was initially developed in the 1970s and 1980s but recent developments in 3D CAD software have allowed building envelopes with complex geometries to be designed more frequently by architects. GFRC is being specified as the main cladding material for these buildings. For larger complex geometry buildings with many, only unique panels, the production of thin-walled GFRC elements was too costly and their production time was not able to meet building time schedules. The outcome has been that the projects being designed originally for thin-walled GFRC have been executed in a different material, e.g. fibre reinforced plastic. This research sought to identify and resolve the key limitations and barriers that prevented thin-walled GFRC from being utilized on these complex geometry building projects.

If complex geometry building envelopes were viewed from the perspective to clad them with GFRC elements then they can be sub-divided into 3 main groups;

- Rainscreens
- Insulated panels
- Integral walls

From the perspective of complex geometries, rain screen panels have the fewest requirements in terms of functionality and should therefore be investigated first. Therefore the focus of this research is on thin-walled GFRC elements as a rain screen. Insulated GFRC panels and GFRC integral walls are outside the scope of this research, because when GFRC elements with complex geometries are resolved for thin-walled GFRC rain screen panels then the technology can eventually be applied to insulated panels and integral walls that have additional and greater functional requirements in terms of weather performance and durability. The main challenge of rain screen panels for building envelopes with complex geometries are that they are often comprised of many unique, non-repeating GFRC elements that require a good surface finish, uniform panel gaps and often significant edge-returns. This requirement for such bespoke free-form GFRC panels cannot be met with the current production methods and existing research also does not describe in detail the aesthetic finish that may be achieved with different existing production methods.

Advancing the edge detailing for complex geometry buildings is also necessary to provide a substantial and monolithic appearance of the building, (14)

§ 1.5 Research objectives

The detailed empirical performance characterization of the limits of functionality and the systematic approach to understanding the use of GFRC in complex geometry facades has not been researched to-date. This research evaluates manufacturing options that allow more design solutions to meet a wider range of architectural intents, enabling more flexible design with free-form GFRC.

This was accomplished by meeting the following objectives:

- Define the limits of free-form thin-walled GFRC cladding panels.
- Identify the key problems that hinder or limit their architectural application.
- Appraise existing free-form thin-walled GFRC edge detailing solutions.
- Develop a prototype mould capable of resolving the restrictions of the state-of-the art in the manufacture of complex geometry thin-walled GFRC panels.
- Identify and resolve the key challenges to enable large-scale manufacture of complex geometry thin-walled GFRC panels.

§ 1.6 Research questions

Main research question:

"How can the manufacture of complex geometry thin-walled GFRC be advanced to meet today's architectural demands?"

Research sub-questions:

1. "What is the state-of-the-art in thin-walled GFRC element production technology?"
2. "What are the key problems associated with realising complex geometry thin-walled GFRC building envelopes?"
3. "What are the key bottlenecks during the manufacture of complex geometry thin-walled GFRC and how can they be resolved?"
4. "How can the solution to these bottlenecks be integrated into a fully automated manufacturing process for complex geometry thin-walled GFRC?"
5. "How can the resulting manufacturing method for complex geometry thin-walled GFRC be developed and tested?"

§ 1.7 Scope of research

The scope of this research focuses on exterior thin-walled GFRC for complex geometry cladding panels used for rainscreen building envelopes as they do not have any weather and water-tightness performance requirements. Insulated GFRC panels and integral walls will be disregarded. The emphasis is mainly on the aesthetic requirements of complex geometry thin-walled GFRC elements, and not the material behaviour of thin-walled GFRC. In architectural design the aesthetic requirements add additional demands to the thin-walled GFRC because visible cracks and glass fibres, and an excess amount of air-bubbles or voids in the visible surface would lead to a rejection of the panels. The research is undertaken predominantly using the European state-of-the-art knowledge base for thin-walled GFRC with visits to manufacturers in Europe and the Middle-east. Interviews with manufacturers in the Far East (China and India) and the Americas have been conducted at conferences, but it has not been possible to visit the Far East and American based manufacturers. Based on the interviews is has been assumed that the knowledge-base in the Far East and the America's are similar to the European knowledge-base. This assumption was supported by information from interviews and review of literature.

§ 1.8 Research methodology

A Outline research phase

The outline research phase was conducted in the research period leading up to the research proposal. An initial literature review and field studies were performed to obtain sufficient information to formulate the problem statement.

- A Initial problem statement
- B Initial literature review and field studies
- C Detailed problem statement (formulation of main research question)
- D Research proposal and research methodology

At the end of the outline research phase the first paper was published in a peer reviewed journal.

B Main research phase

In the main research phase a detail review of the state-of-the-art for complex geometry thin-walled GFRC was completed. This was done with a detail literature review identifying the knowledge gaps in existing research and interviews with manufactures identifying the current productions methods. Collaborations were made with manufacturers to allow state-of-the-art experimental laboratory testing.

The following methods were applied:

1. Review of the state-of-the-art: Detailed literature review, interviews with manufacturers of thin-walled GFRC elements and site visits to buildings with complex geometry building envelopes.
2. Analysis of production methods: Examine production methods, resulting material properties and relative costs associated with the manufacture of complex geometry thin-walled GFRC elements.
3. Experimental laboratory testing: To propose optimal new solutions.

During the main research phase paper 2, paper 3 and paper 4 were successfully published in peer reviewed journals.

C Concluding research phase

The concluding research phase was initiated after the optimal new solutions had been tested for two production methods of thin-walled GFRC. Based on the evaluation of the proposed solution a full scale test of a 10m tall self-supporting shell was made.

1. Evaluation of the proposed solution: Comparing the new solutions with current solutions.
2. Full-scale testing: A 10m tall, self-supporting hyperbolic shell, manufactured and fabricated of 95 thin-walled GFRC double curved elements.

At the end of the concluding research phase paper 5 was submitted to a peer reviewed journal and is currently under review.

§ 1.9 Research task and methodology

For each research sub-question objectives and methodology have been summarised in Table 1.1.

RESEARCH QUESTION	TASK (OBJECTIVE)	METHODOLOGY
Sub-question 1 (Paper 1)	Understand (review) State of the Art	Review literature Industry interviews
Sub-question 2 (Paper 2)	Identify challenges associated with realising complex geometry thin-walled GFRC.	Appraise manufacturing technics Visit to manufacturers
Sub-question 3 (Paper 3)	Determining key bottlenecks for the premixed method	Testing manufacturing process
Sub-question 4 (Paper 4)	Develop for key bottlenecks for the sprayed method	Testing manufacturing process
Sub-question 5 (Paper 5)	Test solutions	Construct the self-supporting Tower

TABLE 1.1 Sub research questions linked to task (objectives) and methodology.

Each sub-question is linked to a peer reviewed paper.

§ 1.10 Thesis outline

This thesis has three main parts. The three parts are linked to the 3 phases identified in the research methodology; the outline research phase, the main research phase, and the concluding research phase. In the three phases five peer reviewed papers were submitted. Each of the peer reviewed papers forms a separate chapter in the thesis together with the introduction and the conclusion.

Part 1 of the thesis shows the state-of-the-art in the manufacture of thin-walled GFRC was collated based on literature review and interviews. The three main production methods for thin-walled GFRC are appraised in Chapter 2 to show the advantages and limitations of each method. The key aesthetic architectural demands are identified, that sets the requirements for the manufacture of thin-walled GFRC for today's architecture.

Part 2 identifies the key problems and bottlenecks for advancing thin-walled complex geometry GFRC. Chapter 3 illustrated the different levels of complexity in geometries used for building envelopes and the change in complexity for thin-walled GFRC panels ranging from a flat panel without an edge-return and a panel offset, to a free-form panel with an edge-return and a panel offset. In Chapter 4 the key bottlenecks that hinder advances in thin-walled GFRC for complex geometry panels using the premixed method were identified and a solution was proposed. Chapter 5 focuses on the entire process of designing, manufacturing and installing thin-walled GFRC for complex geometry envelopes. The barriers and limitations that hinder the process were identified and options to resolve the barriers and limitations proposed. The sprayed method was identified as the most flexible method for manufacturing complex geometry thin-walled GFRC and a solution to advance the manufacture for the sprayed method was proposed.

Part 3 presents the results of the laboratory testing conducted throughout the research. Chapter 6 shows the experimental procedure for thin-walled GFRC, performed for the three main production methods, the automated premixed method, the premixed method and the sprayed method. The final results of the experimental laboratory testing using the proposed solution identified in Chapter 5 were validated by building a 10m tall self-supporting tower, made from thin-walled double curved GFRC elements and the solution enabled the production of a test sample of a double curved element with an edge-return that met the aesthetic demands identified in Chapter 2.

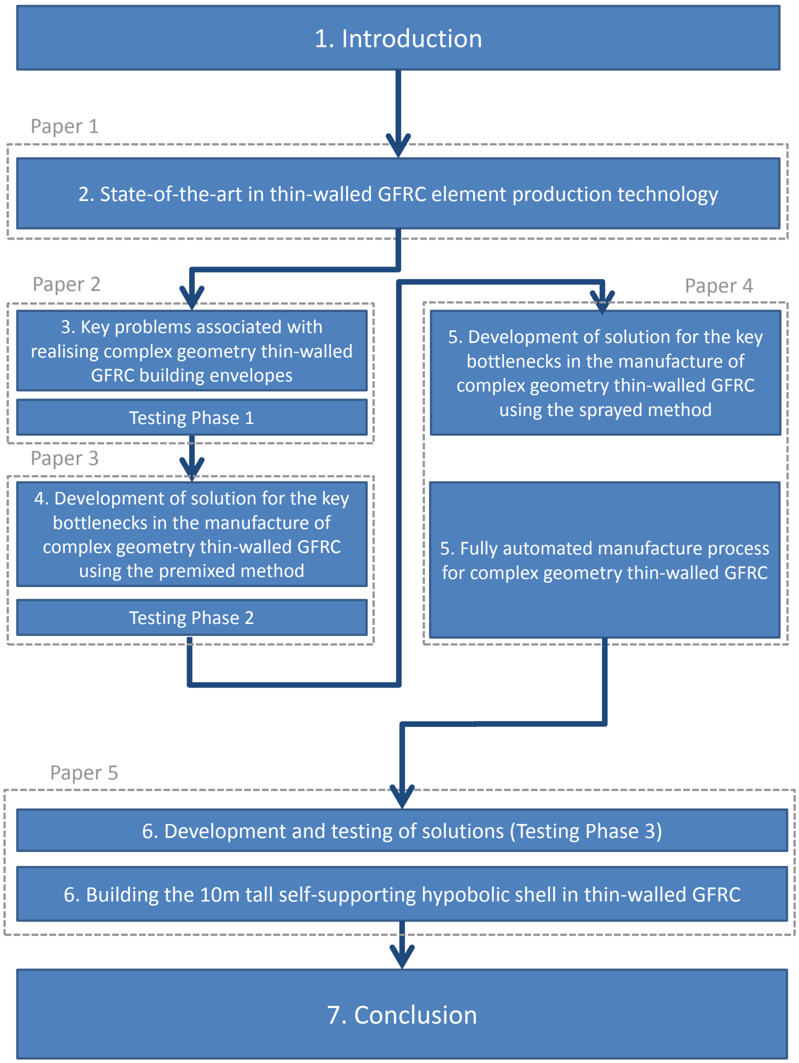

FIGURE 1.10 The dissertation outline and the order of the chapters.

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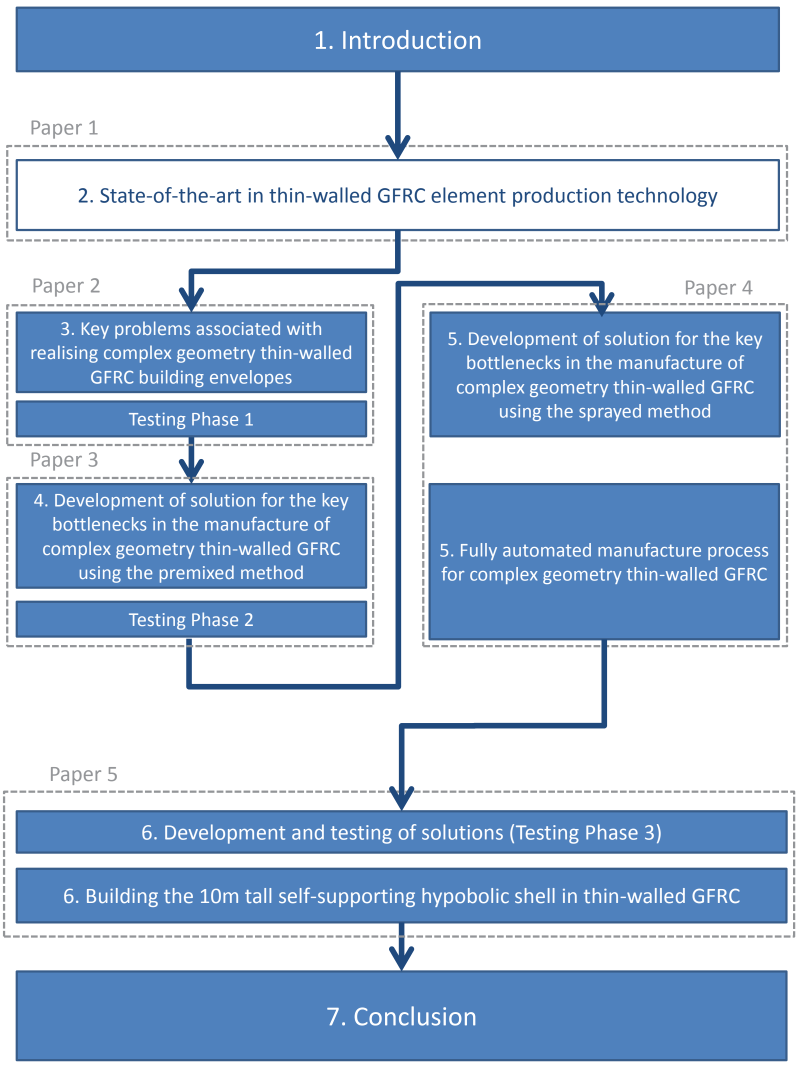
13 *Interview: Intention of architectural appearance of GFRC facades, related to the Kapsarc project in Saudi Arabia.* **Bishop, E.** 2014.

14 **Bishop, Elizabeth.** *Intention of architectural appearance of GFRC facades, related to the Kapsarc project in Saudi Arabia.* [interv.] Thomas Henriksen. 2014.


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

2 Introduction to state-of-the-art thin-walled GFRC

Review of state-of-the-art production methods for GFRC elements and their limitations reveals that new production methods and casting techniques are required to advance thin-walled GFRC for future complex geometry buildings.

Advances in the application of thin-walled glass fibre reinforced concrete elements.

Abstract

Thin-walled fibre reinforced concrete (FRC) elements are being adapted for large scale buildings with complex geometry envelopes. The current production methods, developed in the initial stages of glass fibre reinforced concrete (GFRC) elements in the 1970s, are limited when striving to produce more complex shaped FRC elements. The limitations of the FRC elements in terms of material properties and surface quality are described for these current state of the art production methods. New production methods and casting techniques are proposed that will advance the application of thin-walled FRC for buildings with complex geometry envelopes. Evaluation of the current state of the art production methods concluded that the sprayed GFRC methods are currently the most flexible solution which has the greatest potential for adapting the method to the requirements of complex geometry buildings. Further development of thin-walled GFRC elements would be possible by developing a mould system for complex geometry panels with an edge-return, which can utilise glass fibre reinforced ultra high performance concrete (GF-UHPC) with a vacuum technology, it would be possible to produce complex geometry GFRC elements with an increased material performance and yet still meet the aesthetic requirements of minimal visual defects in the surface of thin-walled elements.

Keywords: GFRC, complex geometry, sprayed method, premixed method.

§ 2.1 Introduction

The ability to sculpt complex geometry buildings with current 3D CAD software has given glass fibre reinforced concrete (GFRC) thin-walled elements a renaissance, with thin-walled GFRC being used as cladding on landmark buildings and architectural infrastructure projects, (1) (2). Methods developed to produce thin-walled GFRC elements in the 1980s did not sufficiently meet the requirements of today's complex geometries in buildings.

Buildings with complex geometry envelopes have been designed with GFRC cladding but difficulties in producing the required complex shapes resulted in alternative material selections. Detailed research exists regarding GFRC and fibre reinforced concrete (FRC) in general, (3), (4) and (5), but there has been less focus on the development of thin-walled GFRC panels. Early design guides for thin-walled GFRC, (6) and (7), are no longer applicable to the demands of today's thin-walled GFRC constructions. Existing research, (4) (8) (9) has not advanced thin-walled GFRC in architectural applications and a systematic approach to applying thin-walled GFRC elements to complex geometry buildings has yet to be developed. This paper will examine the limitations of the current state of the art in thin-walled GFRC production in order to advance and propose new methods suitable for thin-walled GFRC complex geometries. Advances in complex geometry thin-walled GFRC require enhanced methods to produce free-form GFRC panels;

1. with both positive and negative Gaussian curvatures in the same panel,
2. with an edge-return on the panel,
3. where the surface quality of the panel is consistent on the top surface and the sides,
4. with minimal visible pores, voids, and blemishes from air-bubbles formed under the casting process.

An example of a complex geometry GFRC panel is shown in Figure 2.1.

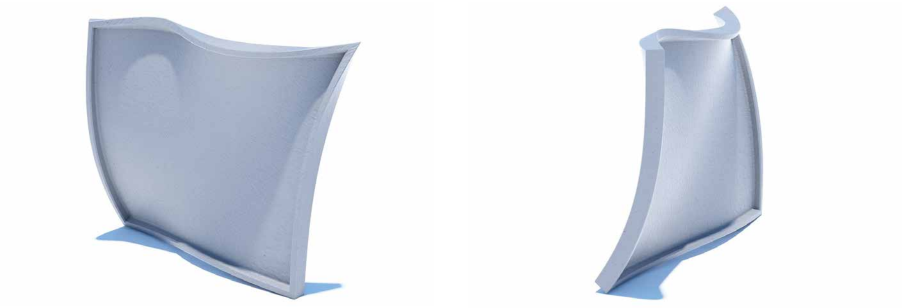


FIGURE 2.1 Renderings of complex geometry thin-walled GFRC.

Enhancing the material properties of the concrete to raise the limits of proportionality will minimise the risk of visible surface tension cracks. This would also allow thinner-walled GFRC panels or allow larger spans between the support points of each panel.

§ 2.2 Thin-walled GFRC elements

Thin-walled GFRC elements, originate from the production of flat cementitious fibre reinforced plates, developed by Ludwig Hatschek, named the Hatschek process (10), which, following a dewatering process, produces a thin-walled FRC element. The fibres used in the Hatschek process were originally asbestos fibres and not easily substituted given the natural compatibility between the asbestos fibres and the cement. Asbestos fibres have now been replaced by mixtures of cellulose fibres and inorganic fibres but such alternatives have limitations dependent on material properties and the methods by which the thin-walled FRC elements may be produced (11) (12).

The thickness of thin-walled FRC elements depends on the production method and if an edge-return is required. For sprayed panels the typically thickness is 8mm – 20mm thick, for premixed panels the thickness are typically 40-60mm thick. Thin-walled FRC rely only on the fibres as the main reinforcement in the post fractured state. Plates thicker than 60mm would normally be considered as conventional reinforced concrete.

Figure 2.2 shows the four main current production methods for thin wall FRC elements and the fibres used in each method. The premixed method and sprayed methods were developed after asbestos fibres were removed from the FRC production process. The premixed method allows most flexibility when using different fibre alternatives to asbestos. With glass fibres it is also possible to use the hand sprayed method to produce thin-walled GFRC elements. Glass fibres have a high tensile strength similar to that of asbestos fibres, and with longer fibre lengths they offer the greatest potential performance for thin-walled FRC elements. Automated spraying methods have improved upon hand spraying to produce high quality textile reinforced GFRC elements (8) that combines GFRC with a glass fibre net embedded in the thin-walled elements.

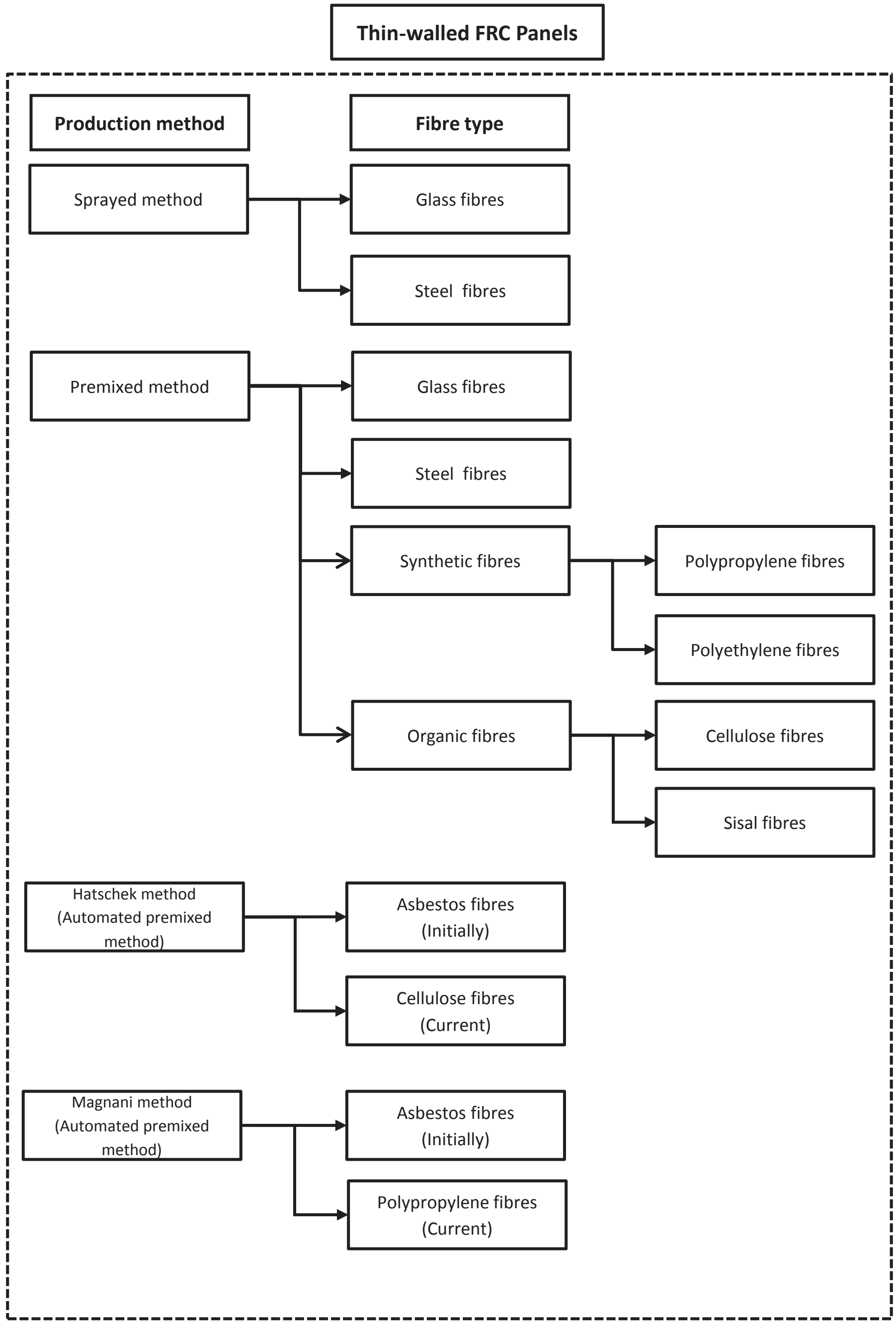


FIGURE 2.2 Production methods for reinforced fibres concrete.

FIGURE 2.3 Automated process for flat thin-walled GFRC.

The limitations of current GFRC manufacture of complex geometry panels are linked to their specific production methods. The sprayed method is dependent on skilled workmanship because the GFRC is applied by hand. Premixed production methods can be automated to advance quality but such methods are currently limited to flat production processes which are vibrated to remove the air-bubbles in the surface. Advancing the material performance overall may be achieved by enhancing the material properties, more controlled curing times, or automation. One method is steam curing, which is used for ultra-high performance concrete (UHPC). The steam curing enhances the tensile capacity up to 34 MPa (13) (14). Figure 2.3 show an automated process for flat thin-walled GFRC.

The methods developed in the 1970s to produce thin-walled GFRC elements were mainly designed for flat panels. Recent developments in complex geometry buildings that require complex geometry thin-walled GFRC elements (15), has placed new demands on the material and required adaptations to the complex forms using existing thin-walled production methods. The Heydar Aliyev Centre (15) was originally designed with a complex geometry comprised of thin-walled GFRC elements. However, the building was completed using thin-walled glass fibre reinforced plastic (GFRP) elements, because the production method for complex geometry thin-walled GFRC elements and the necessary material properties had not been developed to a level, where the cost and the structural performance could compete with more proprietary solutions.

§ 2.3 Glass fibre reinforced concrete

Research into glass fibres reinforced concrete in the 1970s and in the 1980s was pioneered by the Pilkington Brothers Ltd and the Building Research Establishment (BRE), with significant contributions from (16) (17). Since the mid 1980s little research has been published about thin-walled GFRC elements with the most recent publications being the ACI reports (8) (9).

Glass fibres were first introduced into concrete in the 1950s (18) and further developed in the 1960s (19). Initially E-glass fibres (6), were used because of its success in the glass fibre reinforced plastic (GFRP) industry. However, tests with E-glass fibres were problematic due to compatibility problems between the E-glass fibres and the cement (20). Based on the early experience with the E-glass fibre, alternatives were suggested (21), and a new product was developed; Alkali-resistant glass fibres (AR-glass fibres) which combined glass fibres with a zirconia (22). This combination showed greater resilience between the glass fibres and the cement. Other solutions where the cement was changed to an aluminium base were also investigated. However the AR-glass fibres gained wider acceptance in the industry during their early development in the 1970s. The AR-glass fibres have since been further enhanced to the glass fibres used today, (16). The ability to mix the fibres with concrete via spraying allows a high fibre content, (approximately 7%, and a fibre length of 40mm), resulting in a tensile strength of approximately 2 GPa of the glass fibres.

Because of the compatibility problem between the E-glass fibres and the cement alternative fibre materials have been researched resulting in successful alternatives such as polypropylene fibres (23) (24) and steel fibres (25) (26) (27). However these alternatives are also not ideal for thin-walled GFRC. Steel fibres suffer from clustering if the fibres are too long, (generally a problem above 20mm), and if the fibre content is above 2% (3) (28). Polypropylene fibres have a significantly lower tensile strength (4) (29) and do not have the same bonding capabilities between the fibre and the cement slurry (30) (3). The combination of glass fibres and a cementitious mix have a long term effect on the strength of the GFRC elements, and the ultimate capacity of thin-walled GFRC elements is therefore reduced over time. This significantly reduces the design strength of the thin-walled elements.

To compensate for the reduction in strength, steel sub-structures are used to limit the span of thin-walled GFRC elements. The sprayed method allows binders from the sub-structure to be cast into the thin-walled GFRC elements. The differing material properties of the steel sub-structure induce differential thermal movement between the two elements enabling them to move freely without locked-in stresses being introduced in the GFRC. The positioning of binders allows the thin-walled GFRC element to move independently from the steel, which prevents cracks from forming in the surface of the element.

For thin-walled GFRC elements with complex geometries, it is difficult to make a support structure that allows the concrete to move independently from the sub-structure to prevent cracks from forming in the surface. The only exceptions are hyperbolic geometries, where the thin-walled shapes can be formed where the concrete section remains in compression. The limits to the performance of glass fibres and their long term degradation restrict their use for GFRC thin-walled elements. The compatibility between the glass fibres with high zirconia content and the cement has not been developed to a level similar to the asbestos fibres. For complex geometry thin-walled elements with high rates of change in Gaussian curvature, the fibres neither remain straight or perpendicular to potential crack openings, thus compromising the strength of the GFRC element locally, especially in areas of small bend radius. Shorter glass fibres would resolve this issue, but would weaken the bending strength of the complex geometry GFRC element, locally.

§ 2.4 Evaluation of the production methods for complex geometry thin-walled GFRC elements

Two alternative production methods exist when fabricating thin-walled GFRC panels used as flat façade elements, the sprayed method and the premixed method.

The sprayed method, mixes pre-cut glass fibres with the cement slurry, which is sprayed under air pressure. The fibres are sprayed in layers perpendicular to each other and are periodically compressed with small rollers to ensure the fibres are embedded in the cement slurry. This minimizes porosity and enhances the density of the sprayed GFRC.

SPRAYED METHOD	
Advantages	**Disadvantages**
High fibre content	Labour intensive
Controlled fibre distribution	Quality dependent on skilled workmanship
Two dimensional fibre orientation	Manual rollers has to be used to compact the fibres
Consistent surface quality	Low Tensile capacity of concrete
No visual fibres in the surface	
High moment of rupture	
Complex shapes are possible	
Edge-returns are possible	
Reduced voids and air-bubbles	

TABLE 2.1 Advantages and disadvantages using the sprayed method for thin-walled GFRC elements.

Table 2.1 shows the advantages and disadvantages of the sprayed method. The main advantages of this method are the ability to produce a consistent surface finish, with a minimum number of air-bubbles or pores in the surface. However, this method is labour intensive, and requires skilled operators to ensure consistent GFRC quality.

FIGURE 2.4 Typical spraying gun for the hand sprayed method.

Sprayed GFRC panels consist of two layers, a face coat without fibres, (approximately 2 mm thick), and a back coat (mixed with chopped glass fibres), between 8-20 mm thick. The fibre length can be cut to different lengths, (usually between 30-40 mm) with a typical fibre content of 5-7%. The sprayed method allows complex shapes to be produced, in particular edge-returns can be manufactured with the same thickness as the front face of thin-walled GFRC elements, giving flexibility to produce complex geometries (31).

The premixed method, where the fibres are mixed into the cement slurry during the mixing process, allows mixes which are more tailored for the intended use. However, the fibre content usually cannot be higher than 2% and the lengths of the fibres are normally 20 -30mm long. It is difficult to ensure that the fibres are uniformly distributed when the mix is being cast. The mixing process must also be controlled so that the glass fibres do not break during the mixing. It is possible to vibrate the premixed concrete, allowing the mix to become more fluid for a better distribution in the mould (32) (9).

PREMIXED METHOD	
Advantages	**Disadvantages**
Ultra-high performance concrete can be used	Low fibre ratio
Self-compacting concrete can be used	3 dimensional fibre orientation
Mould can be vibrated	Fibre not uniformly distributed
Flat moulds with voids can be used	Flat moulds have to be used
Steel reinforcement can be added	Edge-return difficult to integrate
Less labour intensive	Consistent surface quality is difficult to achieve
	Voids and air-bubbles are difficult to mitigate

TABLE 2.2 Advantages and disadvantages using the premixed method for thin-walled GFRC elements.

Table 2.2 shows the advantages and disadvantages of the premixed method. The main advantage is the ability to control the quality of the cast mix, however premixed GFRC also allows the use of ultra high performance concrete (UHPC) which is not currently feasible with the sprayed method. Glass fibre reinforced ultra high performance concrete(GF-UHPC) was described by Rigaud et al, (33). UHPC has a compressive stress in the range of 140 MPa, and a tensile stress range of 18-20 MPa for normal air cured UHPC. If the UHPC is steam cured the tensile capacity can reach an initial tensile strength of 30-34MPa (13) (14). The advantage of UHPC is the significantly higher tensile strength (34) (35), thus reducing the risk of visual cracks forming in the surface of thin-walled elements in service. However, the low water/cement ratio and the additives in premixed GFRC make the matrix very dense, and this is exacerbated when fibres are added to the mix. The UHPC is costly compared to more conventionally mixes and is mostly not used in the thin-walled GFRC production.

To retain a fluid mix, the fibre content is reduced to 2% to allow the mix to flow into the mould, and reduce the risk of voids and air-bubbles in the top surface of the panel. For complex geometries with premixed concrete a vacuum solution has been developed, (36) and has been used on the Foundation Louis-Vuitton pour la creation in Paris, (2). This vacuum technique allows complex shaped GF-UHPC elements to be produced where entire convex moulds may be filled with the GFRC mix, thereby avoiding air-bubbles and unintended voids. The technique is currently limited to panels of constant thickness, limiting the size of the panels because of the increased self-weight. The glass fibre ratio is limited in the premixed mix, so the limit of proportionality is almost equal to the moment of rupture. This technique has enabled complex geometry thin-walled GFRC elements to be generated with each panel being unique in shape. This has not been achieved before on a building envelope of a similar size.

The automated premixed method, have been developed by specialised manufactures that allow flat thin-walled FRC elements to be produced. Such processes originate from the Hatschek method (10), but it has since been developed further so it can utilize glass fibres for reinforcement.

It is possible to use glass fibre mats, (Textile reinforcement) (37), as the primary reinforcement, thus increasing the ultimate tensile capacity of the thin-walled elements and retains post-fracture integrity, (38).

FIGURE 2.5 Single curved GFRC panels without an edge-return, produced with the automated premixed method.

The panels are produced on special foils that ensure a consistent surface quality of the final panels. The foils allow the thin-walled elements to be formed in their "green-state", i.e. the period after the concrete has been cast and the curing process has begun, but before full matrix stiffness starts to develop. The "green-state" period is dependent on which admixtures are added to the mix, and can be extended by using retarders in the mix. Figure 2.5 shows a mock-up for the Heydar Aliyev Centre produced with the automated premixed method.

The automated process ensures (8) that the quality of the panels, both in terms of the material properties and the surface quality, can be controlled and consistent high quality maintained. A sprayed premixed method has been made possible with the development of new spraying equipment that allows the fibres to be sprayed without damaging them, (39). The sprayed premixed method allows the fibres to be oriented in a similar manner to conventional sprayed GFRC. This result in a higher strength of sprayed premixed GFRC compared to conventional premixed GFRC. It is necessary to control the water/cement ratio because too low a ratio prevents successful spraying and so it cannot achieve the same material properties as conventional sprayed GFRC. The possibility to use GF-UHPC could enable further advances in the use of complex geometry GFRC because of the high tensile capacity of the concrete matrix. The increased tensile strength of the concrete matrix increases the initial performance of the thin-walled GFRC elements.

§ 2.5 Comparing advances in sprayed and premixed GFRC characteristics

The differences in the material properties and surface quality between the sprayed and premixed methods for thin-walled GFRC are compared. The material properties of GFRC are essential to the in-service performance of thin-walled GFRC elements. Table 2.3 shows the relative performance for sprayed and premixed GFRC. The material properties of state-of-the-art sprayed and premixed GFRC has been analysed by Ferrerira et al, (40). The values for the sprayed and premixed GFRC shown in Table 2.3 represent typical values which can be produced, (41) (42). The premixed glass fibre reinforced ultra high performance concrete was tested using a four-point bending test, (33).

	UNITS	SPAYED GFRC	PREMIX GFRC	PREMIXED GF-UHPC
Density	kN/m³	19-21	19-21	24-25.5
Compression strength	MPa	50-80	40-60	170
Elasticity modulus	GPa	10-20	13-18	45
Impact strength	MPA	10-15	8-14	
Poisson ratio		0.24	0.24	
Limit of proportionality (fy)	MPA	7-11	5-8	20 (34 Mpa when steam cured)
Thermal expansion coefficient	10^{-6}/K	7-12	7-12	10-12
Moment of rupture (fu)	Mpa	21-31	10-14	23
Tensile strength	Mpa	8-11	4-7	11

TABLE 2.3 Relative performance of sprayed, premixed, and premixed UHP GFRC.

Table 2.3 shows that sprayed GFRC has better structural material properties than premixed GFRC due to, improved concrete compaction, higher glass fibre contents between 5-7%, and production methods capable of a more consistent distribution of fibres in a two-dimensional build-up. Premixed GFRC is usually limited to a lower fibre content of 2%, the distribution of fibres is more random, and the glass fibres have a 3 dimensional orientation in the matrix that limits the ultimate breaking strength.

GF-UHPC is also a premixed concrete, differing from premixed GFRC in its initial tensile strength of up to 18 MPa (33). GF-UHPC allows an increased initial limit of proportionality, however the low glass fibre content of 2-2.5% and the randomly distributed fibres offer few advantages compared to sprayed GFRC in terms of the ultimate braking capacity (moment of rupture). The higher initial tensile strength of GF-UHPC can be used to reduce visual cracks in the surface of thin-walled panels, while also permitting reduced overall panel thickness. If the UHPC is used with the sprayed method, it would be possible to create a GFRC thin-walled panel with higher tensile capacity compared to sprayed methods used today. Achieving the right material properties requires controlling the concrete mix, so that the properties of the elements in the mix are optimal and that the correct fibre length and content is added into the mix, while controlling the curing process.

During the 28-day curing process, the rate of hydration of the GFRC thin-walled elements diminishes sufficiently to allow it to be considered fully cured. Besides the achieved material properties of the final GFRC elements, the surface quality is essential for thin-walled GFRC elements. The current sprayed and premixed production methods are dependent on skilled workmanship to achieve a sufficient quality of thin-walled GFRC panels. The surface quality is considered in five areas:

1. Smooth texture of the surface
2. No visual fibres in the surface
3. Minimal air-bubbles or voids
4. Consistent colour across all thin-walled GRFC elements
5. No visible cracks

The quality of the mould has an influence on the texture and finished surface quality. Achieving the required surface quality in thin-walled GFRC panels, demands good control over the curing process in the mould. Visual fibres in the surface are predominantly an issue in premixed concrete, where the position of the fibre cannot be controlled. In sprayed GFRC elements, a topcoat is applied without fibres, thus avoiding visual fibres in the surface of the GFRC elements. Air-bubbles are formed during the casting process, where they are trapped in the concrete mix forming voids in the surface or in the matrix, leading to greater porosity of the thin-walled GFRC element.

Colour consistency in the final panels is becoming more important since buildings are being designed with large numbers of thin-walled GFRC panels, (1). Colour consistency may be maintained by producing the same mix and curing it under the same conditions, a difference in panel thickness can later a visual impact on the panel, Thin-walled GFRC elements with a constant thickness would be less prone to discoloration of the fair-face concrete surface (43). With the large quantities of panels required for single projects it is difficult to maintain the same conditions for all panels.

Handling of the thin-walled GFRC panels during the 28 day curing process must be carefully considered, because changes in the environmental conditions or mishandling can cause cracking and affect the colour of the element (44). Visual cracks during the curing process due to creep in the concrete can occur.

Admixtures can be added to prevent visual cracks from creep, but it influences the material properties of the concrete. The handling of the panel under installation, and the long-term support conditions of the panel, pose additional risks of visual crack formation. Figure 2.6 outlines the fabrication processes of thin-walled GFRC, and the inter-related challenges that influence each process.

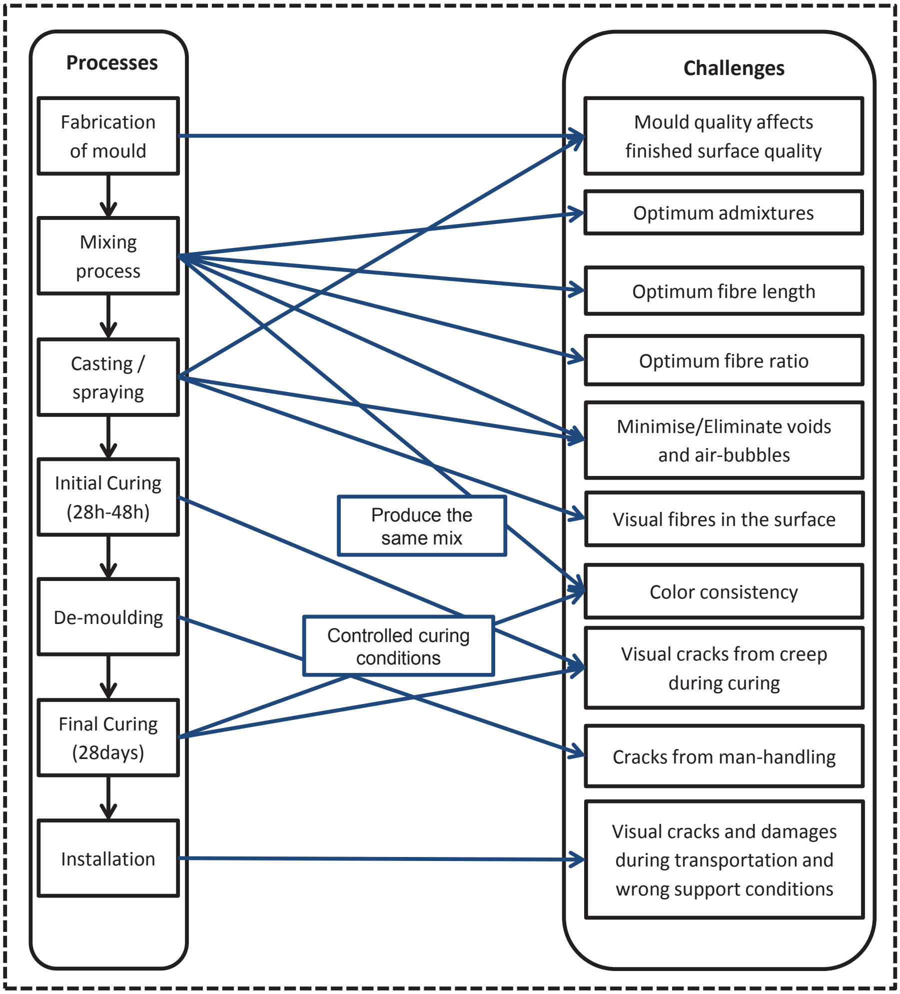


FIGURE 2.6 Diagram showing the link between the processes and challenges for thin walled GFRC elements.

For premixed GFRC, the mixing process is important because poor handling leads to broken fibres, or bundling of the fibres in the mix. Vibrating the mix after pouring it into the moulds reduces the air-bubbles or voids in the concrete, and especially in the surface of the concrete. If the mould is curved it is very difficult to vibrate the premixed concrete without having a horizontal back-surface. In most instances, this makes the premixed method impractical for thin-walled GFRC elements, if it is cast in a mould. A vacuum mould system for thin-walled GFRC elements (36) has been developed to prevent air-bubbles and voids in the surface of the concrete. This is only possible with self-compacting premixed GFRC. To create an edge-return with premixed GFRC, injection moulds are being used, but it is difficult to get all the entrapped air out of the moulds so voids in the surface remain visible after de-moulding. Alternatively the concrete needs to have the same overall thickness for all elements. If the edge-return is >40mm it significantly increases the amount of premixed GFRC and the size of the elements has to be reduced to allow the elements to be handled during transportation and installation.

Sprayed thin-walled GFRC elements require experienced workmanship; to achieve a constant thickness and distribution of the fibres, to ensure the required post cured properties can be achieved. This process is very labour intensive and it is difficult to automate for thin-walled GFRC elements with a complex geometry. With the sprayed method it is possible to create a controlled surface with a minimum of air-bubbles or voids, because a thin top-coat without fibres is initially applied. It is possible to add edge-returns with the same material thickness as the front side of the thin-walled GFRC element. This reduces the weight of the element and it can be transported more easily and handled under installation.

The premixed method is easier to handle than the sprayed method and does not require the same level of experience. If GF-UHPC is used with the premixed method, then it gives a significantly higher initial tensile capacity (limit of proportionality) than can currently be achieved with the sprayed method. With the sprayed method it is easier to avoid air-bubbles and voids in the surface, which reduces the rejection level of the produced thin-walled GFRC elements.

§ 2.6 Recommendations for future production methods

The sprayed method and the premixed method are the two main production methods for thin-walled GFRC. New possibilities with premixed being sprayed (sprayed premix) need to be developed further to understand the impact it will have on the industry, since the technology was introduced in 2008.

A further development would be to spray GF-UHPC. Sprayed GF-UHPC would combine the increased limits of proportionality of UHPC and the high fibre content from the sprayed method, with the possibility of controlling the fibre distribution and orientation, to increase the moment of rupture (Fu). In addition the steam curing of the UHPC is also an option which can increase the initial tensile capacity (13). Steam curing of architectural thin-walled GFRC panels is normally disregarded in commercial productions due to the high additional cost (32). However the self-compacting behaviour of GF-UHPC prevents it from being used at the moment. Complex geometry moulds with vacuum technology using GF-UHPC, would advance complex geometry thin-walled GFRC elements. In order to obtain greater flexibility in terms of geometries, more advanced casting technologies need to be developed and advanced printing technology, currently used for proprietary productions, needs to be further developed to accommodate more complex geometries than single curved geometries.

A similar technology has been developed for the production of sails for international competitions but the challenges of maintaining a high fibre content and controlled fibre orientation, still need to be resolved. Forming the concrete in the production process is an important part of the production, and for flat and single curved geometries, simple timber mould techniques can be utilized. For more complex geometries, CNC milled foam moulds are necessary and new technologies with automatic mould machines have been developed. The challenges with mould machines are the minimum curing time of 24 hours, which prevents the automatic mould from being re-used effectively.

§ 2.7 Conclusion

The history behind fibre reinforced thin-walled elements has been described, in terms of the cementitious mix necessary to produce thin-walled GFRC elements, the fibre lengths and orientation, and the different production methods. The different fibres have been analysed in connection with the production methods for different types of thin-walled FRC. For thin-walled FRC elements the ideal/recommended fibre is alkali-resistant glass fibre, selected for its high tensile strength and the flexibility of the associated production method. Alternative steel fibres are difficult to mix into the cement without causing a balling effect of the steel fibres. This only allows short fibre lengths to be combined with low fibre content in the FRC, limiting the tensile capacity.

The two main production methods used for thin-walled GFRC elements, are the sprayed method and the premixed method. The sprayed method allows greater design flexibility for architectural thin-walled GFRC elements in terms of geometric complexity, when the back-side of the sprayed panels is not visible. With the premixed method glass fibre reinforced ultra-high performance concrete can be used. The advantage of the GF-UHPC is the increased initial tensile capacity. The disadvantage is the high cost of the material compared to typical sprayed GFRC, and the manufacture of the moulds required to create complex shapes with GF-UHPC. For applications requiring large areas of GFRC, a high number of differing elements, and where automated flat GFRC sheets cannot be used, the sprayed method shows the greatest potential. Further development in high strength sprayed GFRC is necessary, with methods of utilizing automatic moulds for creating thin-walled GFRC elements in complex geometry applications. By developing a mould system for complex geometry panels with an edge-return, which can utilise GF-UHPC with a vacuum technology, it would be possible to produce the complex geometry GFRC elements with an increased material performance and yet still meet the aesthetic requirements of minimal visual defects in the surface of thin-walled elements.

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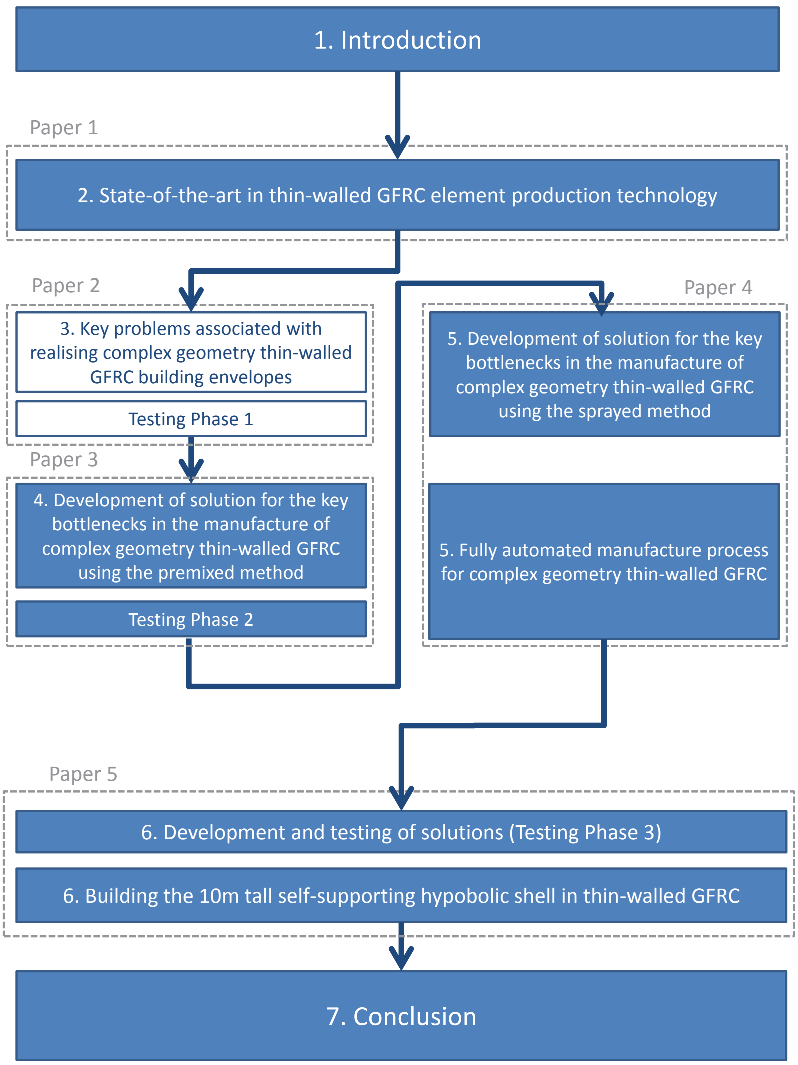
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Paper 2
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3 Key problems associated with complex geometry GFRC

Synthesizes architectural aesthetic demands on existing moulding techniques for complex geometry thin-walled GFRC to allow mapping geometric complexity to the limits of the most appropriate production methods. This defines the main research challenges.

An innovative approach to manufacture thin-walled glass fibre reinforced concrete for tomorrow's architectural buildings envelopes with complex geometries

Abstract

Glass fibre reinforced concrete (GFRC) elements have become a sought after cladding material since their introduction as rain screen cladding for buildings. To advance GFRC for a range of complex geometry building envelopes this also requires advances in existing moulding techniques for thin-walled GFRC elements. To do so it is necessary to define the current state of thin-walled GFRC elements and the constraints and limits placed on them by existing production techniques. This paper identifies the current architectural and aesthetic requirements of thin-walled GFRC elements and maps their range of complexity, from 1-D to 3-D, to the limits of the most appropriate production method. This will inform guidelines for the future design development of thin-walled GFRC and enable an innovative approach to further advance the moulding techniques for thin-walled GFRC elements for a variety of complex geometry building envelopes. The paper concludes on which further steps need to be taken to advance thin-walled glass fibre reinforced concrete for tomorrow's architectural buildings envelopes with complex geometries.

Keywords: GFRC, GRC, complex geometry, bespoke, edge-returns, flexible moulds, thin-walled

§ 3.1 Introduction

Glass fibre reinforced concrete (GFRC) elements have become a sought after cladding material since their first introduction as rainscreen cladding for buildings. The first buildings in the UK with GFRC cladding were designed in the 1970s. These buildings were designed with geometrically simple GFRC elements based on a flat building pattern. As building envelope geometries become more complex the aesthetic demands of designers become more challenging. This chapter presents an innovative approach to the manufacture of GFRC as façade cladding for buildings with a range of complex geometries. The current state-of-the -art in terms of thin-walled GFRC elements with complex geometries, and the production methods that can be used to achieve the intended panel geometries, are defined, but the structural performance of the thin-walled GFRC elements is outside the scope of this paper. The intent is to define guidelines for an innovative approach to advance thin-walled GFRC elements with complex geometries. An illustration of the scope of the work presented in this chapter is highlighted in Figure 3.1.

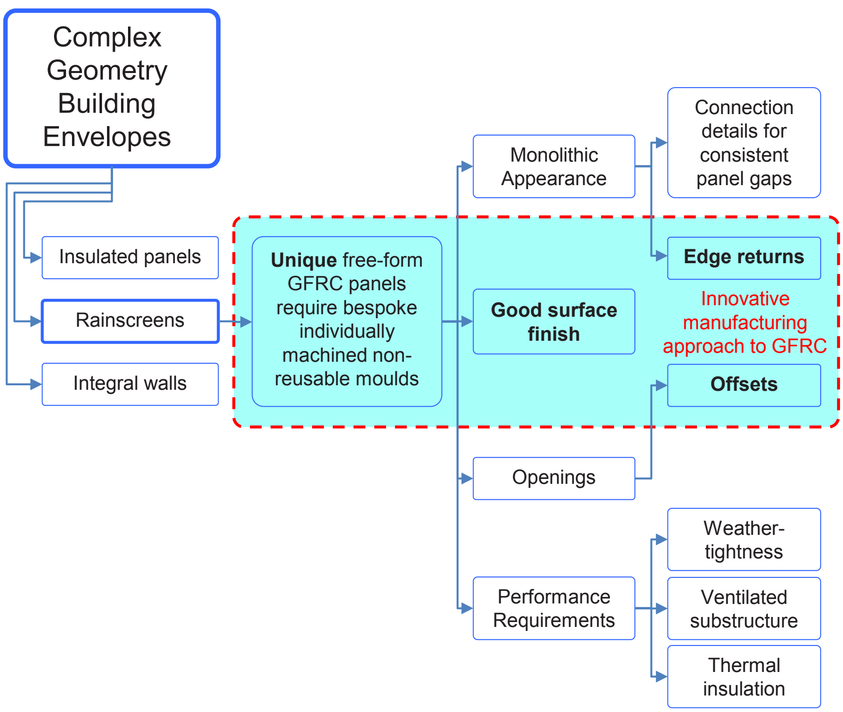


FIGURE 3.1 An innovative approach to the challenges of complex geomerty GFRC rainscreen cladding.

If complex geometry building envelopes were viewed from the perspective to clad them with GFRC elements then they can be sub-divided into 3 main groups;

- Rainscreens
- Insulated panels
- Integral walls

The focus of the presented research is thin-walled GFRC elements as a rainscreen. Insulated GFRC panels and GFRC integral walls are outside the scope of this research, since GFRC elements with complex geometries first need to be solved for thin-walled GFRC elements before the technology can be applied to insulated panels and integral walls. The main challenge of rainscreen panels for building envelopes with complex geometries are that they are often comprised of many unique, non-repeating GFRC elements that require a good surface finish, uniform panel gaps and often significant edge-returns (edge-returns are shown in Figure 3.2 and in Figure 3.6). This requirement for such bespoke free-form GFRC panels with good surface quality, edge-returns and panel offsets (a panel offset is shown in Figure 3.3) cannot be met with the current production methods and existing research also does not describe in detail the aesthetic requirements that may be achieved with different production methods.

FIGURE 3.2 Corner of a GFRC panel with an edge-return, the GFRC panel has been produced with the premixed method

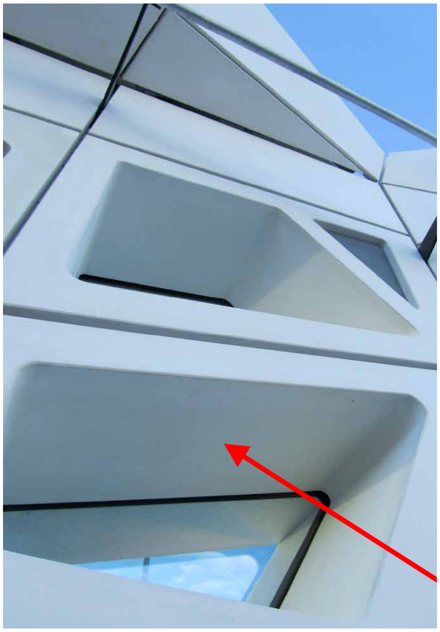


FIGURE 3.3 GFRC element with a panel offset at window return (indicated with red arrow) to allow for a window recess, produced using the premixed method.

Advancing the edge-detailing for complex geometry buildings is necessary to provide a substantial and monolithic appearance of the building, (1). The edge-return is defined as an up-stand from the edge of the panel as shown in Figure 3.2. If GFRC elements have an edge-return or a panel offset, (required for openings), from the primary surface in addition to a complex geometry, then the manufacture of the GFRC element is even more complex.

This last requirement for edge-return detailing for thin-walled GFRC is currently costly and time consuming for buildings with complex geometries and little or no repetition of the unique free-form elements. A more cost-effective innovative approach is proposed that enables many unique thin-walled GFRC elements of complex geometry with edge-returns and panel offsets to be manufactured while providing a good surface finish with more complex forms and more robust edge detailing.

The offset of the surface required for openings, is defined as a cut out in a surface that is translated parallel to the primary surface, as used in the King Abdullah Petroleum Studies and Research Centre in Riyadh, Saudi Arabia (2) and on The Broad Museum, in Los Angeles, USA (3). An example of a thin-walled GFRC element with an offset developed for the King Abdullah Petroleum Studies and Research Centre is shown in Figure 3.3.

Identifying the most appropriate production method (sprayed, premixed, or automated premixed)[1] is key to the technical viability of the proposed innovative approach to the manufacture of GFRC for tomorrow's architectural buildings envelopes with complex geometries. Fabrication of the thin-walled GFRC panels with edge-returns and offsets cannot be achieved by all production techniques so the limitations of each production method and the potential panel geometries are defined and illustrated systematically.

The current challenges in production methods and enhancements to the edge detailing required to advance complex geometry thin-walled GFRC elements are to:

1. Identify the hierarchy of 1, 2, 3-D and free-form geometries that will inform the scope of the shapes that a mould must be capable of forming.
2. Evaluate the range of edge-returns and panel offsets that may be accommodated so that the resultant complex geometry thin-walled GFRC elements may be sealed effectively yet allow movement, while also maintaining a monolithic appearance.
3. Map the range of available GFRC manufacturing processes to the hierarchy of panel geometries of increasing complexity and optimally match each to the proposed moulding process.

1 The most common production methods are the sprayed method, the premixed method and the automated premixed method. The different production methods for thin walled GFRC are described in in detail and compared in (13) (31) (29) (18)

Achieving such manufacturing flexibility will enable advances in thin-walled GFRC elements for complex geometries to meet the future aspirations of designers and architects.

§ 3.2 Architectural application of 1, 2, 3-D and free-form thin-walled GFRC

Thin-walled GFRC as an architectural cladding material has been used since its initial development in the 1970s (4). The material was used because it was a durable and relatively lightweight weather-resistant material that could easily be handled. It could also be easily moulded to specific dimensions and shapes, and the cost of producing the elements was low compared to similar durable materials such as glass. (With glass it was not possible to fabricate the edge-returns and panel offsets required to obtain a monolithic appearance of the building.) Such properties made thin-wall GFRC a sought after material with the first examples produced as modular elements at 30 Cannon St building in London, UK in 1977, and, the UOP Fragrance, Tadworth, Surrey UK in 1978 (5). In the last decade thin-walled GFRC has been used for landmark buildings with complex geometries because of the introduction of advanced geometric software tools capable of creating such free-form building envelopes (6).

Thin-walled GFRC elements are predominantly used as rainscreen cladding because a thin (10-20mm) non load-bearing element can be handled easily. Thin-walled GFRC elements are single units that are fixed to a sub-structure, such as the Expo Bridge in Zaragoza, Spain (1996), and the Soccer City stadium in South Africa (2010). However, for the Heydar Aliyev Center, Baku, Azerbaijan (7) thin-walled GFRC was initially proposed for its complex free form geometry but due to the complexity of the geometry all panels 1m above the concourse were produced using GFRP (Glass fibre reinforced plastic) panels, i.e. the majority of the single curved panels, double curved panels and free-form panels on the building. The panels on the concourse including 1m of the building were produced with GFRC, but consist of mainly flat geometries (8). The cladding material was changed due to the high cost of producing many bespoke complex geometry thin-walled GFRC panels. Figure 3.4 shows the production of the GFRP panels for the Heydar Aliyev Center.

FIGURE 3.4 Production of GFRP cladding panels for the Heydar Aliyev Center

Other recently built examples of rainscreen GFRC cladding is the newly opened museum Foundation Louis Vuitton in Paris, France (2014) (9). A further two landmark buildings in the Middle East are under construction, the King Abdullah Petroleum Studies and Research Centre in Riyadh, Saudi Arabia (2) and the Qatar National Museum in Doha, Qatar, both with GFRC clad areas of approximately 100.000m^2. All these examples exhibit different geometric complexity, some with solely thin-walled flat GFRC panels **without** an edge-return, and others with thin-walled free-form GFRC panels, **with** an edge-return.

In order to distinguish between different complex geometry thin-walled GFRC elements it is necessary to classify their shape in terms of their complexity and also the range and scope of their associated manufacturing process possibilities. A detailed description of the geometric categories of thin-walled GFRC elements is described by (10), (11), (12) and (6). The range of geometries were divided into 4 categories;

1. Flat surfaces
2. Single curved surfaces
3. Double curved surfaces
4. Free-form surfaces

Single curved and double curved geometries have additional sub-groups depending on the severity of curvature and their rate of change in curvature. Table 3.1 shows the geometric forms with associated examples of GFRC clad buildings or sculptures using thin-walled GFRC elements.

TOC

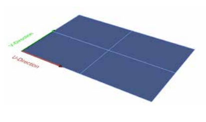
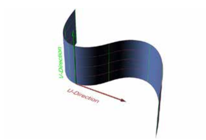
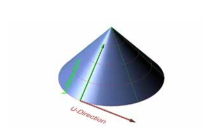
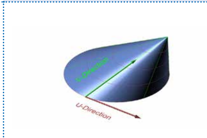
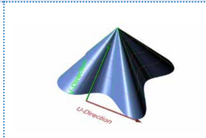
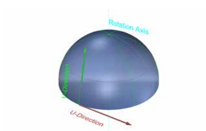
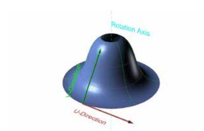
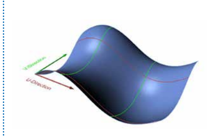
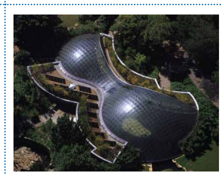
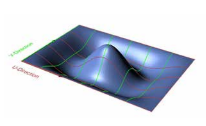
FLAT SURFACE	 Flat surface			
				
SINGLE CURVED SURFACE	 Single curved surface	 Simple cone surface	 Tilted cone surface	 Cone-like surface
				
DOUBLE CURVED SURFACE	 Spherical surface	 Rotational surface	 Translational surface	
				
FREE-FORM SURFACE	 Truly free-form surface			
				

TABLE 3.1 Geometric forms with associated examples of GFRC clad buildings or sculptures with thin-walled GFRC elements

As the demand for a wider range of complex geometry buildings increases the production technology and the digital machining tools required to produce the GFRC elements is not advancing at the same pace, thus hindering further advancements. Any new approach to advance the design and production of GFRC panels with complex geometries requires a new moulding technique able to produce thin-walled GFRC panels capable of forming all 4 different surface categories. The manufacturing complexity, (the cost, the severity of curvature and their rate of change in curvature), ***increases*** as the design progresses from flat towards more free-form surfaces. Conversely the degree of potential repetition ***decreases*** as the design moves from flat to more bespoke free-form panels. This complexity matrix is shown in Table 6 The increase in complexity for thin-walled GFRC panels ranging from flat panels to free-form panels combined with the changes in geometric shapes and requirements for an edge-return and offsets in the surface († no panel exist with this geometry).

Where a single * represents a simple flat thin-walled GFRC panel without an edge-return or panel offset. Increasing numbers of asterisks represents the increase in complexity of the geometry, and ******* represents the most complex double curved or free-form thin-walled GFRC panels with an edge-return and a panel offset with changing curvature in the same element.

COMPLEXITY TABLE	Homogenous surface	Edge-return	Panel offsets	Constant curvature	Changing curvature	Changing curvature, Edge-return, Panel offset
Flat	*	**	**	†	†	†
Single curved	**	***	***	****	*****	******
Double curved	***	****	****	*****	******	*******
Free-form	****	*****	*****	†	******	*******

TABLE 3.2 The increase in complexity for thin-walled GFRC panels ranging from flat panels to free-form panels combined with the changes in geometric shapes and requirements for an edge-return and offsets in the surface († no panel exist with this geometry).

Table 3.1 identifies the hierarchy of 1, 2, 3-D free-form geometries with real built thin-walled GFRC envelopes. This allows these geometries to be mapped to their increasing geometric complexity as shown in Table 3.2.

§ 3.3 Challenges in edge detailing and sealing of thin-walled GFRC

GFRC as building façade cladding is used in contemporary architecture, and its ability to be formed easily and adapted to complex shapes makes it a sought after material. However, the technology to manufacture the complex shaped elements has not followed the development in 3D CAD software tools. The challenge lies in the edge-return detailing of the GFRC elements to act as an architectural device, designed to hide the sub-structure when the joints between the GFRC panels are viewed from obscure angles, and make the façade appear substantial and monolithic (1). Figure 3.5 illustrates an edge-return in the red square compared to GFRC panels without an edge-return, shown in the red oval marker, where the metal sub-structure is clearly visible. However, an edge-return can be difficult to produce for all envisioned geometries, both in terms of cost and minimal defects in the surface (13).

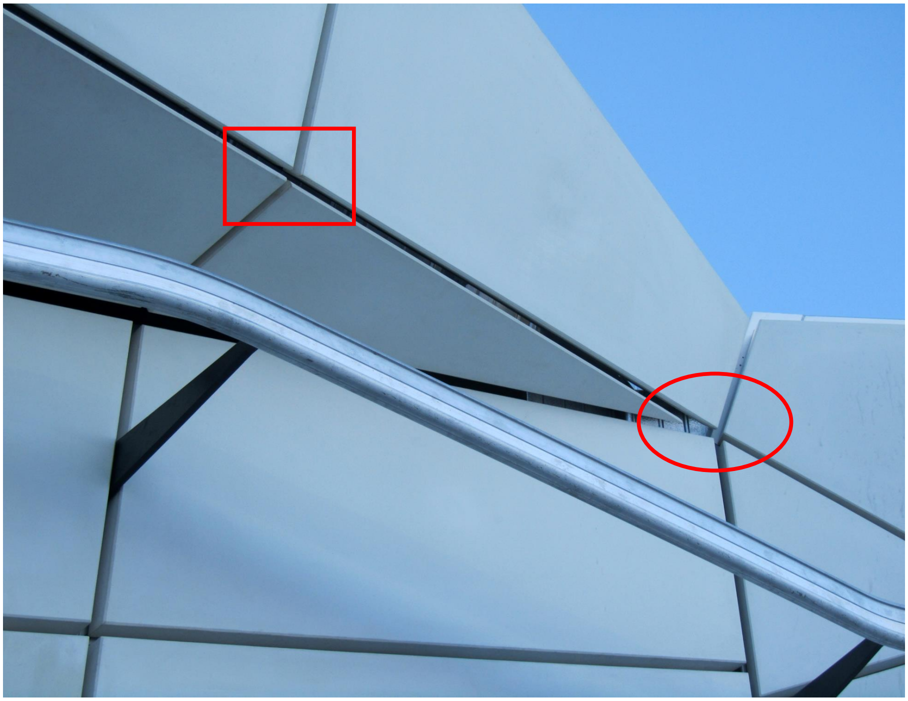


FIGURE 3.5 The difference between GFRC elements with an edge-return and without an edge-return. In the red squre the edge-return hides the substructre from obscure angles making the building's cladding appear substantial and monolitic, where the GFRC elements in the red circle does not have an edge-return and the sub-structure is visible.

The feasibility of an edge-return depends on the production method. For a flat GFRC panel produced using an automated premixed method such as the Hatschek process (14), or similar production methods (15), an edge-return can only be achieved by folding the panel in its "greenstate" (13). Figure 3.6 shows a flat GFRC element produced using an automated premixed method without an edge-return and a GFRC element produced using an automated premixed method ***with*** an edge-return. The edge-return has been created by folding the edge of the flat GFRC in the "greenstate" of the concrete (13).

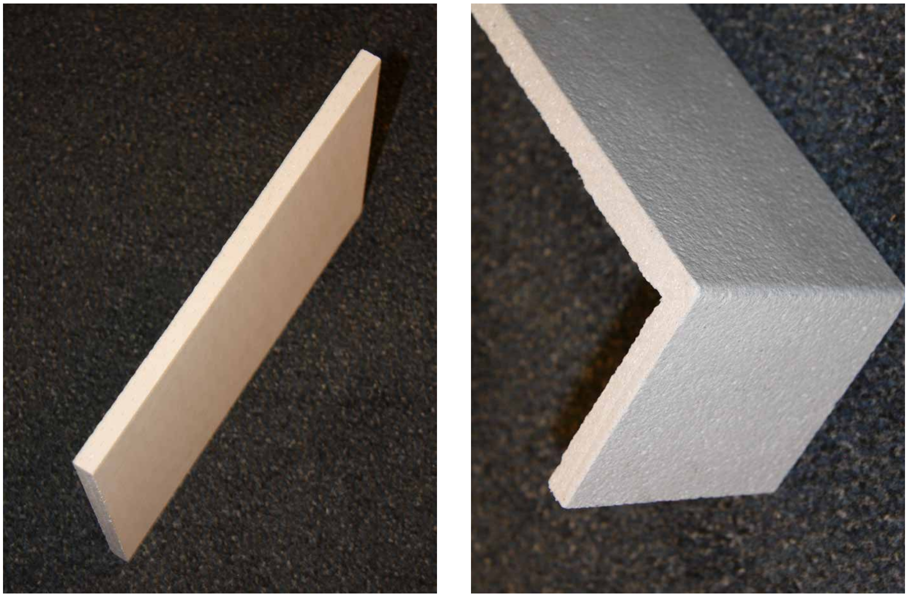


FIGURE 3.6 GFRC produced using an automated premixed method elements without and edge-return, and a GFRC element with an edge-return both elements folded in its "greenstate".

Producing an edge-return by folding the GFRC in its "greenstate" using automated premixed limits bending capacity in the fold and would need a mechanical bracket fixed to the inside of the panel to prevent the edge-return from breaking under handling and installation of the panel. The feasibility of manufacturing edge-returns is also dependent on the geometry of the panel. An edge-return using thin-walled GFRC panels therefore provides the optimum design solution in most cases because it resolves the visual demands for a monolithic appearance while allowing the cavity between adjacent GFRC elements to be closed.

The detailing between the joints is the main problem for rainscreen cladding for all geometries since the joint needs to accommodate:

- the panel edge-return;
- the connection to the substrate;
- water tightness of the joint line;
- ventilation of the cavity space behind the GFRC;
- if required, the conflict between having a ventilated cavity space while simultaneously providing sand tightness.

The edge detailing of thin-walled GFRC elements governs the final visual appearance of a GFRC panel and can be divided into two sub-groups, open joints and closed joints.

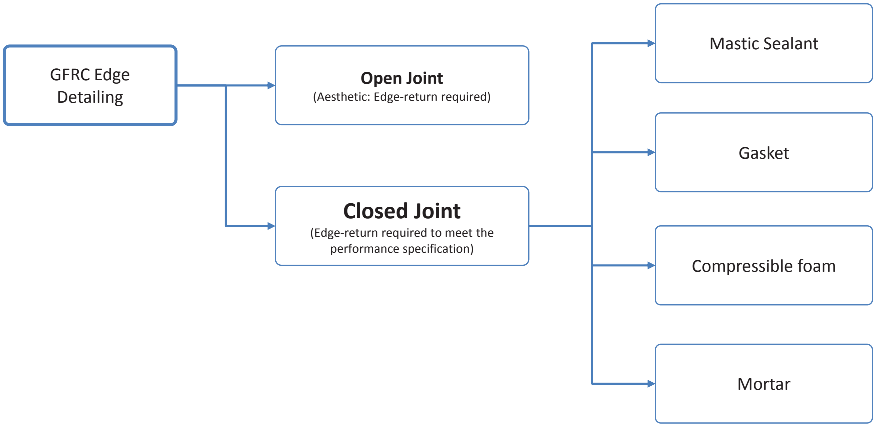


FIGURE 3.7 The sub-groups of open and closed joints for GFRC edge detailling.

GFRC edge detailing with a closed joint is designed to prevent rain and infestations entering the cavity, and to provide a primary water-tightness barrier. This allows the secondary water-tightness layer to be re-solved using a membrane system. To close the joint between the GFRC panels, several solutions as shown in Figure 3.7 may be used, namely;

- Mastic sealant
- Gasket
- Compressible foam
- Mortar

Such solutions can accommodate the relative movement between GFRC panels [2]. The mastic sealant is the most flexible solution; however they have a limited service life and need to be maintained frequently to retain their adhesive performance. Additionally mastic sealant might not be compositionally compatible with GFRC. In this case a primer needs to be applied to the edge of the GFRC panel to seal the GFRC before the mastic sealant is applied to prevent the mastic sealant from migrating into the GFRC. Gasket and compressible foam solutions both have weaknesses at the intersection between the horizontal and vertical joint lines, where it is difficult to make a water-tight connection[3]. For GFRC façades which require a closed joint system and, where the façade geometry is free-form, it is difficult to use another solution other than mastic sealant to achieve a water tightness seal, since the gasket and the compressible foam will have to be twisted along the joint lines, which is not possible unless they are produced with a very precise geometry.

The requirements of edge detailing for thin-walled GFRC elements to make the façade appear monolithic and at the same time fulfil specified performance requirements can be resolved by incorporating an edge-return. For facades with open joints this resolves the aesthetic requirements and a closed joint facade allows sufficient space to make a seal between the adjacent panels. In some cases a closed joint between adjacent panels is not feasible because in hotter climates the cavity under the GFRC panels needs to be ventilated to reduce the heat build-up under the GFRC panels, thus restricting the use of fully sealed joints between two panels.

2 When using mastic sealant, compressible foam or mortar to close the gap between adjacent panels, the aspect ratio between the depth of the thin-walled GFRC panel and the distance to the adjacent panel must be sufficient to accommodate the sealing material, with a typical minimum depth of 20 mm. Since thin-walled GFRC elements are produced typically with a thickness of 10-20mm, (if using the sprayed method) (13) (31) (29) they require an edge-return capable of accommodating the sealing joint between the panels. Thin-walled GFRC panels produced using the premixed method (13) (31) (29) (18) usually result in constant thicknesses of 40-60mm, which makes an additional edge-return unnecessary for the purpose of closing the joint between the panels.

3 Using a gasket, (typically silicone or an EPDM based gasket), the joint can be closed by pressing a gasket between the panels. This usually requires that the edge-return of the panels have a groove that keeps the gasket in position after it has been installed. Using a gasket, it is also possible to make a closed joint with a system similar to a standard stick system, where the back edge is compressed against a gasket. The gasket is prefixed to the secondary structural system before the GFRC panels are secured into position.

§ 3.4 Matching available thin-walled GFRC manufacturing processes to increasing complexity of panel forms

The demand for more unique GFRC panels has been driven by the development of geometric software tools for the building industry (6). Current production methods for thin-walled elements in complex geometries cannot meet this demand so this must be resolved to advance thin-walled GFRC elements further. For free-form building geometries such as the Heydar Aliyev Center, Baku, Azerbaijan (7) the scope for panel repetition was very limited because each individual thin-wall GFRC element shape and their fixing positions were defined explicitly. The production tolerances of the elements had to remain within span/1000 (16) to accommodate the tolerances in the secondary support structure. The connection brackets used for the cladding on the Heydar Aliyev Center (See Figure 3.8) between the secondary support structure and the GFRC elements could accommodate a range of tolerances in the X, Y & Z planes, however the need for accurate manufacture of the GFRC element was paramount.

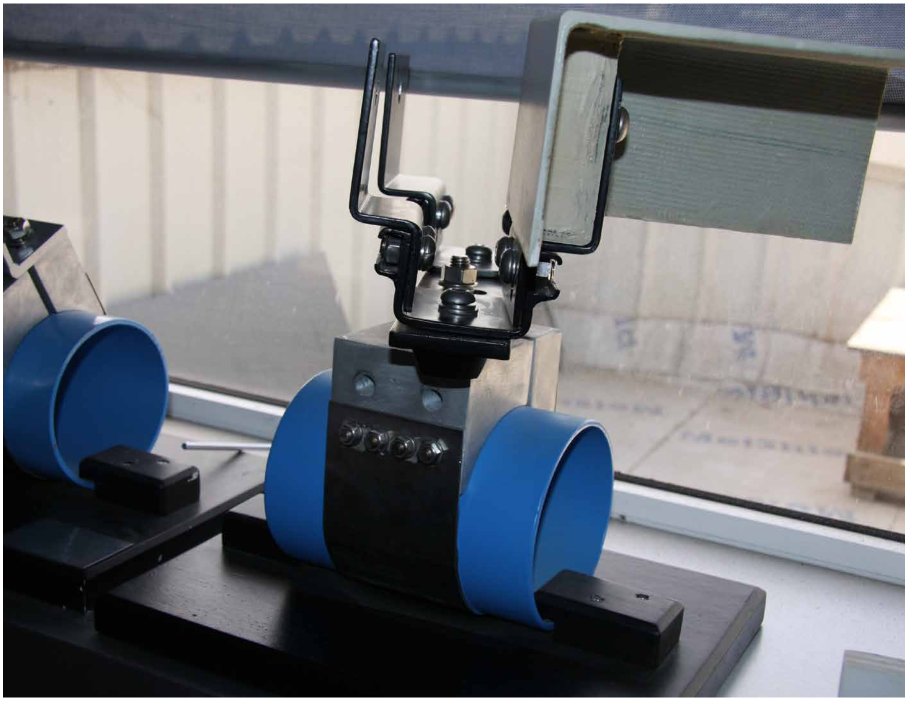


FIGURE 3.8 The connection between the secondary steel and the GFRP panels used on the Heydar Aliyev Center, which enables to accommodate tolerances between the secondray sub-structure and the complex geometry panels.

The possibility to adapt GFRC to complex geometry envelopes depends on the level of complexity as described in Table 6 and the requirements to the edge detailing of each thin-walled GFRC element. Each geometric category of thin-walled GFRC panel, (flat, single, double and free-form) may be divided into sub-groups dependent on the edge detailing and panel offsets in the element.

- GFRC panels without an edge-return
- GFRC panels with an edge-return
- GFRC panels with an offset (panel offset)
- GFRC panels that are folded

The different production methods for thin-walled GFRC panels have limits in terms of which edge-return can be produced. For flat GFRC panels without an edge-return, all 3 standard methods, sprayed, premixed and automated premixed, may be used for their manufacture as shown in Table 7.

PANEL GEOMETRY	EDGE DETAILING	PRODUCTION METHOD		
		Sprayed	Premixed	Automated premixed
Flat	Without edge-return	√	√	√
	With edge-return	√	√	
	With panel offset	√	√	
	Folded panel	√		√
Single Curved	Without edge-return	√	√ (large radii)	√
	With edge-return	√	√ (uniform thickness)	*
	With panel offset	√		
Double Curved	Without edge-return	√	√ (large radii) †	*
	With edge-return	√	√ (large radii) †	
	With panel offset	√		
Free form	Without edge-return	√		*
	With edge-return	√		
	With panel offset	√		

TABLE 3.3 The limitations in GFRC production methods for the different geometric panels († Double curved premixed thin-walled panels with an edge-return are only possible in a double-sided mould. * Advances required in the automated premixed method to strive towards a fully digital complex geometry GFRC element process)

The automated premixed method is limited to simple geometries; however, if it was possible to produce complex geometry moulds it would theoretically be possible to "print" the GFRC matrix directly onto the mould, thus utilizing the automated premixed GFRC with higher quality and lower cost compared to the sprayed method. Adding an edge-return, or a panel offset to the GFRC element, limits the production possibilities to the sprayed or the premixed method. For flat folded panels where the GFRCs panels are folded in their "green-state" this is only possible with the sprayed and the automated premixed method.

§ 3.5 The limits of current production methods for the thin-walled GFRC elements.

The automated premixed method, the premixed method and the sprayed method each have their different limitations depending on the level of geometric complexity, visual quality of the surface finish and the material strength. The geometric limitations for the 3 production methods are shown in Table 3.3. Table 3.4, Table 3.5 and Table 3.6 show how the different panels would look depending on the method by which they are produced. The automated premixed method has the most limitations in terms of geometric complexity, edge-returns and offsets. With the premixed method geometric shapes may be achieved if using a double-sided mould. This technique was used to produce the LRT Station Canopy in Shawnessy, Calgary, Alberta (17). However, in principle the premixed method is limited to panels with constant thicknesses if they have a complex geometry. The sprayed method has few limitations in terms of the geometric shapes that can be achieved but are limited by the material properties (13) and the sprayed side of the panel has a rough unfinished texture.

§ 3.5.1 Automated premixed method

The automated premixed method is predominantly used to produce flat GFRC sheets; however it is possible to form the sheets as they leave the production line when they are still in their "greenstate" (13) . The automated premixed method has limitation on which geometric shapes can be achieved. Table 3.4 shows the panel geometries that can be achieved with the automated premixed method i.e the Hatschek method (14) or similar automated premixed methods (15) (18):

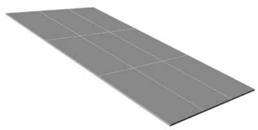
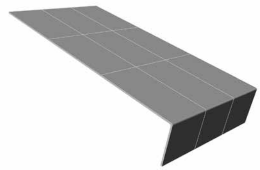
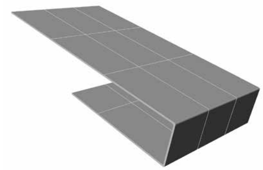
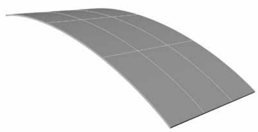
	AUTOMATED PREMIXED METHOD		
	Without edge-return	With edge-eturn	Folded
FLAT PANELS			
SINGLE CURVED		*	*
DOUBLE CURVED	*	*	*
FREEFORM	*	*	*

TABLE 3.4 Thin-walled GFRC elements produced with the automated premixed method (* These panels will create a fold in the surface if they are folded)

The Hatchek method was designed to produce flat thin-walled fibre reinforced Concrete (FRC) panels. However, an edge-return can be created by folding the sides of the flat sheet, but the fibre orientation limits the bending strength of the folded corner. External mechanical fixings are necessary to prevent the edge-return from breaking off. This folding technique allows a cube to be formed from a flat sheet of GFRC when the sides are folded in the concrete's "greenstate". It is possible to produce a single curved element without an edge-return from the GFRC panel using the Hatchek method, including all the single curved cone geometries shown in Table 3.1. Single curved elements with an edge-return would have to be folded in their "greenstate", however this would create ripples along the fold line and the upper surface of the single curved cone surface would no longer be in the same plane.

Producing double curved and free-form elements using the automated premixed method would also create folds in the main surface as shown in Figure 3.9. The uncured material from the automated premixed method would have to contract locally to accommodate the change in curvature; this is not possible with the Hatschek method (14) or the modified Hatschek method (15). Therefore the automated premixed method is currently limited to simple shapes.

§ 3.5.2 Premixed

Thin-walled GFRC elements produced with the premixed method require double-sided moulds to create the intended shape. For geometries without an edge-return such thin-walled elements are usually produced with a constant thickness over the entire panel. The panels are usually produced in thicknesses up to 60mm, which effectively present an edge-return (9). Thin-walled GFRC panels with a constant thickness of 40mm-60mm are very heavy and difficult to man-handle through fabrication, transportation and installation. Panels using the premixed method that need an edge-return or a panel offset require a two-part mould with a positive and negative element, where the premixed GFRC is injected into the mould cavity. To maintain an acceptable surface quality without too many blemishes, and to avoid balling of the fibres, it is necessary to have a very fluid GFRC mix (13). The most successful way is to inject the GFRC from the bottom of the mould with the visual surfaces facing downwards, and slowly fill the mould with GFRC.

Table 3.5 illustrates the variations of premixed thin-walled GFRC elements used in architectural complex geometry buildings. It shows the elements that can be produced with current techniques, most commonly milling the moulds with a 3D CNC machine, (3).

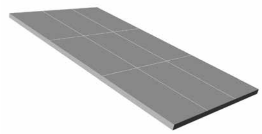
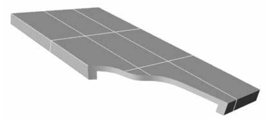
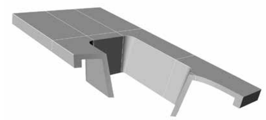
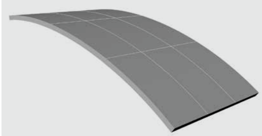
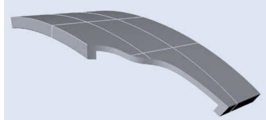
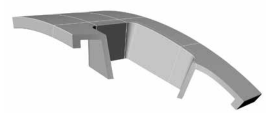
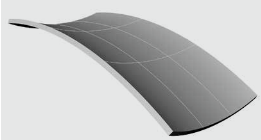
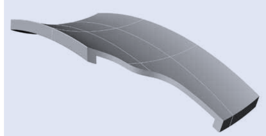
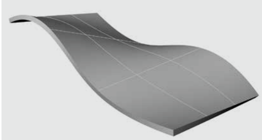
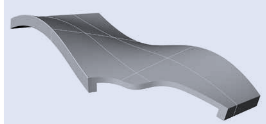
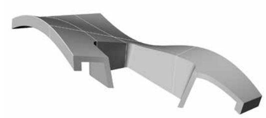
	PREMIXED METHOD		
	Without edge-return	With edge-return	With a panel offset
FLAT PANELS			
SINGLE CURVED	Possible with double sided or vacuum mould 	Possible with constant wall thickness <60mm 	* 
DOUBLE CURVED			* 
FREEFORM			* 

TABLE 3.5 Thin-walled GFRC elements produced with the premixed method (* Panels are difficult to produce with the current production methods).

However, this method is slow and costly given the milling time required to make the moulds. It is also not cost effective to produce the many unique elements using the premixed method demanded by large buildings with complex geometry panels (7). Finally it is a challenge to completely mitigate air voids and blemishes in the surface using the premixed method, leading to a high rejection rate, (4) (19).

From the range of geometric types and shapes, only some of the edge-returns and panel offsets shown in Table 3.5 are possible using current casting technologies. The flat shapes can be cast in a mould with a positive and a negative side, including those with an edge-return and a panel offset. The panels produced for the King Abdullah Petroleum Studies and Research Centre in Riyadh, KSA (2), were finally produced using the sprayed method. For single curved, double curved and free-form panels, this is only realistic with a constant thickness, using a vacuum mould system (20), and is currently limited to larger radii and single curvatures. This method was used successfully for the Foundation Louis Vuitton in Paris, France (9).

The premixed method is dependent on the mould system to create the intended shapes. For single curved, double curved and free-form elements an additional vacuum system needs to be applied to ensure the concrete flows into all parts of the mould without leaving any surface voids.

§ 3.5.3 Sprayed method

Thin-walled GFRC elements produced with the sprayed method also require a mould, but the mould is simpler compared to the mould system necessary for a thin-walled elements produced with the premixed method. The sprayed method requires a negative mould to allow the intended shapes to be produced making it more cost effective and with a smaller rejection rate compared to the premixed method (13) (4). The different types of elements that may be produced using the sprayed method are shown in Table 3.6. The flat elements without an edge-return or panel offset are the most simple to produce. The production of a mould for double and free-form shapes is complicated and is currently mainly only produced via milling of the mould in a CNC machine.

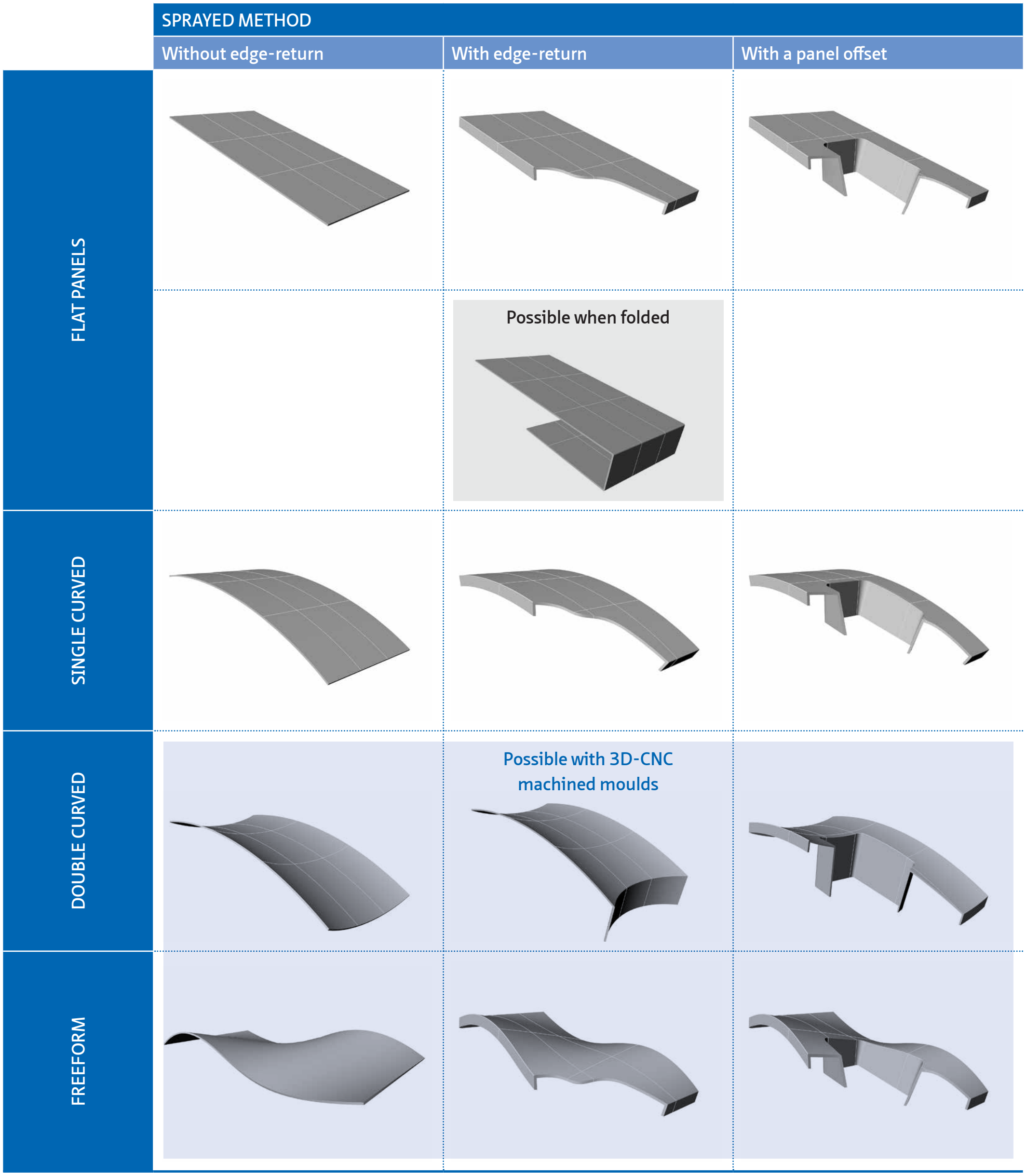


TABLE 3.6 Thin-walled GFRC elements produced with the sprayed method.

The sprayed method also allows the sprayed GFRC element to be folded in its "greenstate", but this method also allows additional GFRC material to be sprayed into the folded corner to increase the material thickness, thus increasing the moment capacity of the folded side for out of plane forces.

The sprayed method has the most flexibility in terms of achieving different shapes and panel offsets as shown in Table 3.6. Given the variety of possible geometric complexity, shapes, edge-returns and panel offsets, almost all contemporary architectural buildings could be realised with an exterior GFRC rain-screen cladding. What currently prohibits this is the ability to produce moulds with the intended geometry and successfully casting the GFRC elements with an acceptable surface quality.

The sprayed method allows a face coat to be sprayed initially without any fibres (13) to minimize the number of air-bubbles and blemishes and visible fibres on the front surfaces of the thin-walled GFRC element. The disadvantages are that the back of the panel will have a rough appearance compared to a premixed panel produced with both a positive and negative mould. The spraying method is not the limiting factor because sprayed cementitious material relies on ordinary portland cement (OPC) or else the cement does not remain in place after it has been sprayed on the return edges of the sprayed mould or on the sides of the offset. Advancing the cementitious material for the sprayed method is difficult without using UHPC, however currently UHPC is to similar to self-compacting concrete and would not stay in place on sloped surfaces when being sprayed, and difficult to apply via spraying for non-flat shapes. New technologies for spraying UHPC are being developed at the moment (21) (22), however they have not been used commercially. Current moulding systems are restricted and costly so to advance the application of thin-walled GFRC elements for complex geometries an innovative approach to the manufacture of the moulds systems must be developed.

§ 3.6 Innovative approach to the manufacture of thin-walled GFRC

Thin-walled GFRC is currently typically fabricated with wooden moulds and predominantly using the sprayed method but such moulds can only be used for flat, single curved geometries and double curved geometries with large radii. For more complex geometries CNC machined moulds must be used, but are costly and take a long time to manufacture. These can only be reused for a limited number of cycles, increasing the need for additional moulds, so a new method has been explored that could potentially reduce the time and cost to produce moulds for complex geometry GFRC. Recent developments have focused on making flexible tables able to accommodate the demand for ever-changing geometries by allowing a digitally generated shape to be formed, (23) (24). To prevent shrinkage cracks forming during de-moulding, and to maintain colour consistency of the thin-walled GFRC, it needs to remain in the mould for the initial curing period. When testing a flexible table at an automated premixed production line shown in Figure 3.9, it became apparent that the flexible table alone would not resolve the demand for the number of moulds necessary to produce many different unique panels at the same time. Therefore the flexible table process was advanced to create moulds able to generate the intended form when the final shape of the panel, with edge-returns and panel offsets, had been determined. This innovative new mould casting system will enable many unique shapes to be fabricated while still utilizing the costly flexible table to its full potential, all within a 30 min cycle.

The innovative approach to advance GFRC panels with complex geometries involves 3 stages.

- Determine the shape of the GFRC element
- Generate the intended shape on a flexible table
- Cast the mould on the flexible table

The first step is necessary to transform the design intent into a buildable solution, since many initial free-form shapes used in architecture only showcase the initial layer of the surfaces and not at this stage in the design development solving the joint width and the offset of the panels in terms of the edge-return and the panel offset openings (as shown in Figure 3.3). The detailing between the top surface and the angle of the edge-return is paramount for the fabrication and the complexity of the production of free-form panels. The second stage forms the correct geometry on the flexible table and projects the correct geometry of the panel on the table, allowing the correct angle of the new mould to be formed. The third stage is the new casting method for the new mould, using a fast curing expandable material. Ideally this would be a sustainable organic material, with a low environmental impact. Initially a self-expanding foam was used as shown in Figure 3.10. Stage two and stage three forms the basis of the new innovation. The main reason for introducing these additional steps is that the flexible tables are unsuitable for the economic mass production of thin-walled GFRC elements as they are very costly, and many tables were needed to produce element for projects as the Heydar Aliyev Center. Figure 3.9 shows a flexible table with a free-form shaped top surface. A thin-walled GFRC panel has been placed on the table, still in its “greenstate”.

FIGURE 3.9 Testing of a thin-welled GFRC panel produced with the automated premixed process on a flexible table. The flexible table is positioned in a free-form shape

The proposed new approach adds an additional step in the process to allow the full benefits of a flexible table to be realised so that the cast mould can be used in the production of the full range complex geometry GFRC elements as shown in Figure 3.10.

FIGURE 3.10 The proposed new approach which adds an additional step between the flexible table and the casting of the GFRC element.

With further development of the approach it would also be possible to solve the issue of manufacturing GFRC with edge-returns and panel offsets. The edge-returns can be created by making an offset on the flexible table before the new mould is cast. However further research must be undertaken to find sustainable materials for the mould system that also meet the requirements of a continuous surface with rapid production and low cost to advance the architectural application of thin-walled GFRC.

§ 3.7 Conclusion

Aesthetic development of contemporary architecture demands building envelopes of complex geometries and GFRC often is the desired cladding material for such complex geometries. However, the manufacturing processes of thin-walled GFRC elements for complex geometries have not kept pace with this demand. This paper has appraised the challenges of the design of complex geometry buildings using thin walled GFRC panels. The full range from facetted buildings with flat GFRC panels with high repetition, to the most complex geometries with many unique free-form panels are considered. To ensure a substantial and monolithic appearance of the building, the edge-detailing of the thin-walled GFRC panels becomes very important.

The edge-detailing with different GFRC panel geometries are mapped to their optimal production methods for the appropriate edge-return of a thin walled panel.

From the categorization it can be seen that the automatic premixed method and the premixed method currently restrict the shapes, edge-returns and panel offsets that can be produced. The innovative approach using a flexible table allows custom made moulds to be produced, thus avoiding the milling of the complex shaped moulds, making complex geometry GFRC more cost effective. The proposed new approach adds an additional step in the process to allow the full benefits of a flexible table to be realised so that the cast mould can be used in the production of the full range of complex geometry GFRC elements. This will advance the architectural application of thin-walled GFRC in the future.

The next challenge lies in developing a new moulding system further to accommodate all 3 production methods and produce a mould that can be reused while achieving the required surface quality. Future research will look into developing the method for a new mould system to allow both the sprayed method and the premixed method to be used.

§ 3.8 References

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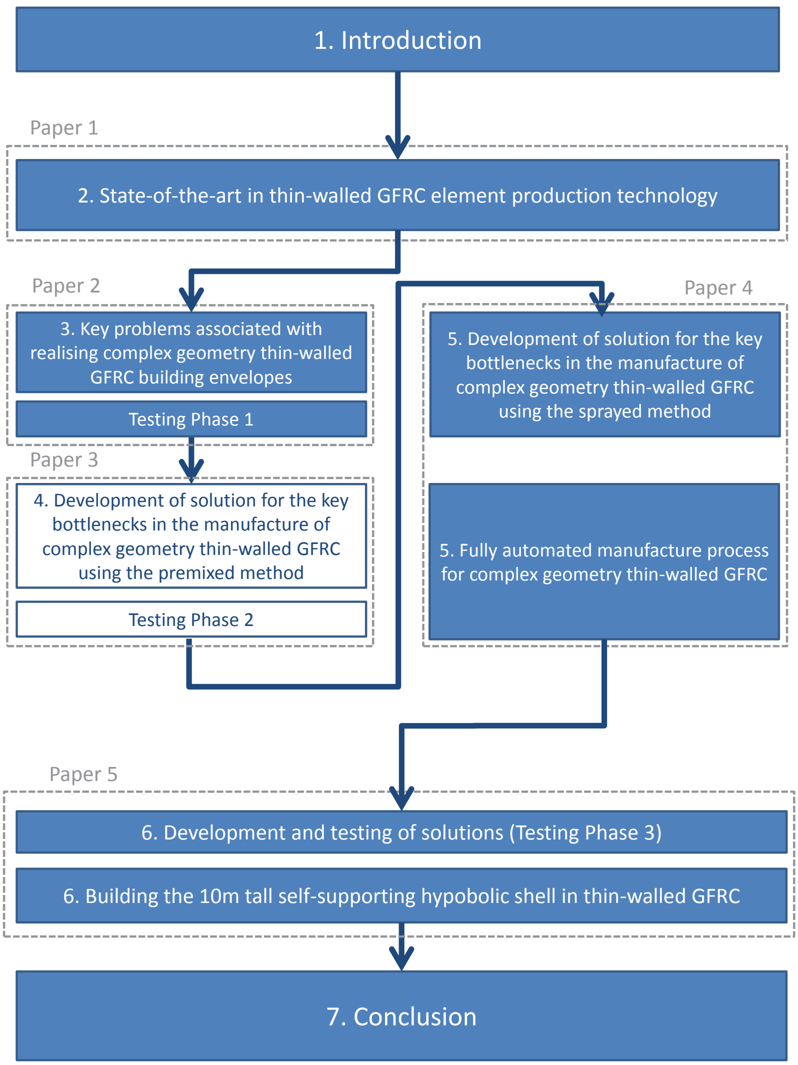
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4 Developing a solution for the premixed concrete method and proposing a step by step fabrication process.

Proposed new step-by-step fabrication process for complex geometry thin-walled GFRC elements using more cost effective large-scale production methods to bridge the gap between the limited capabilities of current solutions, and the architectural aesthetic demands for good surface quality, with the option of having an edge-return/ panel offsets and the same surface quality as the front surface to give a monolithic appearance.

A new method to advance complex geometry thin-walled glass fibre reinforced concrete elements.

Abstract:
Complex geometry concrete is being used in building and infrastructure projects however, costly in-situ mouldings are necessary to achieve these geometries. Advancing discretised concrete shell structures requires the development of a new moulding system at lower cost and reduced mould production times. Future thin-walled glass fibre reinforced concrete (GFRC) elements must possess good continuous surface quality, with the required edge-returns and panel offsets, combined with the physical material properties to increase spans and lower the risk of visible surface cracks. Existing moulding systems do not have the capability to meet these contemporary architectural aesthetic and design aspirations. A new mould system to produce free-form thin-walled GFRC elements is presented and can be used to replace CNC milled moulds for the manufacture of thin walled GFRC. Such a system allows the mould for thin-walled GFRC elements to be produced in a fast, cost effective and more efficient manner. A new step-by-step process to achieve such new thin-walled GFRC panels is described, permitting the fabrication of complex geometry thin-walled GFRC elements using more cost effective large-scale production methods. This process bridges the gap between the limited capabilities of current solutions, and the architectural aesthetic demands for good surface quality, with the option of having an edge-return and the same surface quality as the front surface to give a monolithic appearance.

Keywords: GFRC, Complex, geometry, flexible, casting, moulds

§ 4.1 Introduction

Complex geometry concrete used in many building and infrastructure projects require costly and time-consuming in-situ concrete mouldings to achieve these geometries, such as those developed by Nervi, Candela, Torroja, Isler (1) (2) (3) (4) (5). In an attempt to advance discretised shell structures (6) (7) it has been shown (8) that it would require the development a new moulding system with reduced costs and mould production times. Existing research on glass fibre reinforced concrete (GFRC) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) forms the basis for this paper to advance concrete shell structures and thin-walled façade elements

The full design aspirations of complex geometry buildings are not currently being met by current thin-walled glass fibre reinforced concrete (GFRC) façade elements because of limitations in the fabrication possibilities. Future GFRC elements must possess good continuous surface quality, with the required edge-returns and panel offsets, (required to allow openings), combined with the physical material properties to increase spans and lower the risk of visual surface cracks.

Attempting to produce many such, often unique, individual GFRC panels using current manufacturing techniques is too time consuming to fabricate in a cost effective manner. Existing moulding systems and recent digital flexible tables are examined and compared to highlight their shortcomings in meeting the requirements of future GFRC elements. This chapter then proposes a new moulding system that resolves the deficiencies of existing systems, both in terms of design requirements, low cost and high-speed production capabilities.

The new moulding technique permits the use of the premixed method and its inherent advantages that utilize the material performance of ultra-high performance concrete (UHPC), except for panels using the sprayed method (15).

This moulding technique uses two layers of polyurethane foam with a high density foam (37-38kg/m^3) at the surface to minimize damage from casting, and a low density foam core (15-16 kg/m^3) below, where merely support is needed. It also allows the mould to be reused for more casting cycles. This not only allows the system to be re-used but the lower overall density of the foam incurs less cost. This is more sustainable than current CNC milled foam materials where the form material has a constant density. Furthermore the new moulding technique would allow integration into an automated premixed method for a more streamlined fabrication process for thin-walled GFRC elements. An overview of the key problems and limitations in the production of complex geometry thin-walled GFRC elements with offsets and edge -returns are examined to inform the production capabilities required by any new moulding system.

§ 4.2 State-of-the-art GFRC elements

GFRC has traditionally been used for flat cladding panels, however, GFRC is currently very popular in contemporary iconic modern architecture and is now being built with cladding formed from double-curved geometry GFRC. The ability to shape many unique concrete panels in a simple, cost effective manner allows these more demanding architectural aspirations to be met. Spraying is currently one way to form GFRC panels into a complex geometry, and if applied correctly, the quality of the panels can be controlled and a high surface quality achieved. This method was applied to part of the Heydar Aliev Cultural Centre in Azerbaijan (19) and to the Etihad museum in Dubai, currently under construction, however, due to the cost and the geometric complexity, the remaining double-curved wall panels were produced in glass fibre reinforced plastic (GFRP) on a one-sided mould.

Architecturally aesthetic demands require building envelope panels to have a perceived depth to make the façade appear monolithic (20) (8). This can be resolved by adding an edge-return to the panel. To achieve this today for complex geometry panels, produced using the premixed method, it is necessary to produce a panel with a constant thickness of 40-60mm over the entire panel.

Double curved GFRC panels with small radii, such as spherical surfaces, are difficult to produce because it is necessary to cast the panels in special moulds. Such moulds today are typically produced by CNC milling of lightweight foam blocks, or similar, to form the intended geometry. One recent alternative is a dynamically reconfigurable surface (a digital flexible table with actuators and a surface membrane) (21), however, GFRC requires an extended curing time during which the mould remains static, thus limiting them to one thickness of panels. In a-state-of-the-art building with double curved GFRC, such as the Louis Vuitton Foundation in Paris (22), the panels were produced with the premixed method using a flat vacuum moulding technique that was moved in its "greenstate" (8) onto a shaped sub-surface and then cured. The panels had a constant thickness to accommodate an edge-return.

§ 4.3 Existing moulding systems for GFRC

To enable the development of a new mould system it was important to understand the limitations and advantages of existing mould systems used for thin-walled GFRC panels. The main challenge with current mould systems is their ability to create an edge-return and a panel offset for complex geometries.

The ability to make edge-returns and offsets in the mould required for complex geometry thin-walled GFRC is currently not possible due to the limitations of current production methods for thin-walled GFRC elements that require a good surface quality. Currently the mould for complex geometry envelopes is the main bottleneck in the production of thin-walled GFRC panels so any new mould system must address this problem.

During the research for new mould systems it became apparent that the cost of the current moulds was an important part of the overall cost of a complex geometry GFRC building. However, current indicative costs for the different mould techniques are either not available or out of date. In this research 3 established GFRC manufactures in Europe, Denmark (23), Germany (24) and the UK (25), were interviewed to determine the approximate cost of current mould production. The costs were indicative and could vary from continent to continent. The costs shown in Table 4.1 are for single sided moulds so for double sided moulds the cost would have to be doubled. Such current indicative costs will be used for guidance when estimating the cost of producing complex geometry GFRC panels.

Existing mould systems that are able to produce complex geometry thin-walled GFRC elements can be divided into the following categories, (23) (24) (25):

MOULD TYPE	LABOUR INTENSITY	MATERIAL COST AND LABOUR COSTS *	MOULD PRODUC-TION TIME	REUSABILITY **	COMMENTS
Wooden moulds (limited to single curved and large radii (r > 0.5m) double curvature)	Medium	Material 25€/m²; Labour 40€/h	2-4h/m²	1-20 times	Sometimes a structural calc. for a timber mould is also required (con-crete-pressure and weight). This adds additional cost.
Steel moulds	High	Material approx. 50€/m²	5-8h/m²	20-500 times	Steel moulds are used when it is required to have a seamless appear-ance, largest size 400 x 600cm.
Rubber moulds	High	Material 80-200€/m²	3-5h	10-50 times	Must be applied to a timber mould. Limited sizes.
Polystyrene foam moulds, wire cut	Low	Material will be calc. in m³ foam. approx. € 30,-/m³	1 h	5-30 times	Standard Polysty-rene foam-block is 120x120x500cm, Significant waste
3D computer nu-merical controlled (CNC) milled moulds (Foam ,Plastic)	Low	300-400€/m²	5-10 h	5-10 times	The moulds are typically made from foam or plastic. Timber or metal alternatives can also be used. The quality of the mould depends of the quality of the foam or plastic. Limited sizes
Flexible tables with pistons	Low	High Machine cost,	20 min	Motors 10.000 times Surface 100 -500 times	Limited sizes approx. 1m x 2m
Flexible tables with actuators and membranes	Low	High Machine cost	5 min	Motors 10.000 times Surface 500 times	Limited sizes currently approx. 1.2m x 1.2m

TABLE 4.1 Existing mould system to produce then walled GFRC (*Prices are 2016 estimates, **Depends on the mould geometry)

The capabilities of existing moulding systems are, in general, limited;

- by the complexity of the geometric shapes they can produce
- by the demands to make edge-returns and panel offsets as part of a continuous surface
- to less unique panels with significant repetition
- by the high cost of reconfiguring for more unique shapes
- by the extended curing times required for concrete.

Existing moulding systems for thin-walled GFRC are traditionally made out of wooden moulds or bespoke steel moulds if much repetition is required (26). However, the wooden moulds are usually only available for flat or single curved geometries with large radii (r > 0.5m) (27). For double curved wooden moulds the wooden surface sheet must be sufficiently thin to enable ease of forming. This technique is not cost effective for the production of thin-walled GFRC with little or no repetition. The range of current mould types are illustrated in Figures 4.1 to 4.8. Figure 4.1 show a single curved sprayed GFRC element with a constant radius. Figure 4.2 shows a single curved wooden mould with a cone like geometry (8), and the mould is being prepared for curing of the sprayed GFRC.

FIGURE 4.1 Single curved sprayed GFRC element on a wooden mould

FIGURE 4.2 Wooden mould with a double curved surface. The double curvature is possible because of the big radii

Rubber moulds are an alternative method of casting thin-walled GFRC and are used for GFRC elements with special features, making very fine and detailed surfaces possible. To produce a rubber mould an initial "negative" mould must be manufactured to produce the "positive" rubber mould, which, again is not cost effective unless there is significant repetition. Building more unique thin-walled GFRC with little or no repetition requires a different moulding system and rubber moulds to make textured surfaces possible due to the casting techniques of the rubber moulds, which is difficult to achieve with other mould types. Figure 4.3 shows a rubber mould with a wooden texture.

FIGURE 4.3 Flat rubber mould with a texture finish

FIGURE 4.4 Single curved polystyrene mould

Closed cell extruded polystyrene foam moulds are another method of producing moulds since the mould material is cheap. For single curved geometries (8) the polystyrene foam can be cut easily with a computer guided hot wire cutter to give the intended shape (28). This method is limited by the ability of the hot wire cutter to only produce a positive mould. Figure 4.4 shows a polystyrene mould used for single curved thin-walled GFRC produced with an automated premixed process. The moulds have been cut with a hot wire cutter but are limited to ruled surfaces. It is possible to create complex and very precise shapes using a robot arm together with a hot wire cutter (29).

Figure 4.5 shows a robot guided hot wire cutter, which can be used to make high precision moulds.

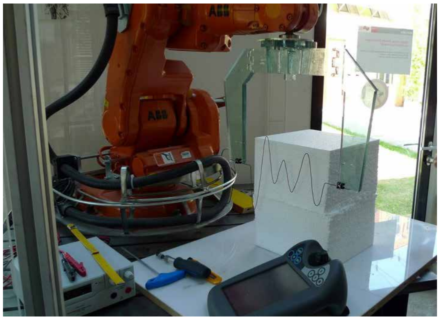

FIGURE 4.5 Computer controlled hot wire cutter

FIGURE 4.6 Finished art project, where the GFRC elements has been cured on hot wire cut polystyrene

CNC milled moulds are used currently for complex shaped GFRC elements and can be produced using plastics, foams, mood or metals. Such moulds are costly compared to other moulding systems, however, currently there are few alternatives. The milling process incurs significant material wastage and the size of the moulds is limited by the size of the milling machines. CNC milled moulds can be used for more complex forms and it is possible to make a mould with recesses that can be used to cast almost any shape. The main limitation of the CNC milling process is the time it takes to mill the surface and the limited quality of the milled surfaces (30). Moulds for thin-walled GFRC are shown in Figures 4.7 and 4.8.

FIGURE 4.7 3 axes CNC machine

FIGURE 4.8 Concrete mould milled by a CNC machine

Such a time consuming milling process increases the cost of milling a mould compared to those made from timber so alternative moulding systems are being sought (31). The new proposed mould system for complex geometry thin-walled GFRC panels (8) is one such alternative to using CNC milling of moulds.

§ 4.4 Digital moulding technique for complex geometry GFRC

The early development of discretized double curved concrete was pioneered by the completion of the Sydney Opera House (32) and Heinz Isle's development of hyperbolic concrete shells (3). Renzo Piano followed these developments by suggesting an alternative apparatus to make double curved surfaces (33) but limitations in technology at the time halted further progression. More recently the development of digital parametric design has evolved to a level where it is possible to digitally determine shapes and curvatures (34) (35) (28). This led to digital flexible tables that could be automatically adjusted to meet intended shapes but they were limited to low rates-of-change in curvature. The sailing industry was the first to introduce a digital flexible table for the production of fixed sails for racing yachts (36). Digital flexible table technology for the architectural industry was introduced in 2007, aimed at double curved glass production (37) but because the process of bending glass required high temperatures, the technology at that time was not ready for the production of such double curved glass. Subsequent flexible tables, more suited to double curved concrete (38), were then proposed for 3 dimensional concrete. Such digital flexible tables can be divided into two categories;

- Digital flexible tables with pistons
- Digital flexible tables with actuators and a surface membrane

Digital tables based on piston-actuated surfaces were comprised of small pistons but could not form a continuous surface, have been proposed (39) (40), so are not suitable for "prestigious" concrete surfaces. A digital table using pistons with a membrane was proposed in 2010 (41), and had the ability to make offsets in the surface, however, the profile of the top of pistons could still be seen through the membrane and became visible on the concrete surface.

Digital flexible tables with actuators and a surface membrane for free-form concrete surfaces were proposed in 2006 and further developed in 2010 (38)) (21) (42) and could be computer-controlled. The surface was able to form continuous shapes by manipulating support points and could be used for casting various materials on the surface. Such a system is shown in Figures 4.9 and 4.10.

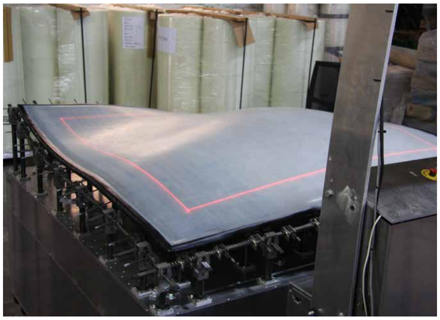

FIGURE 4.9 Digital flexible table with actuators and membrane positioned to give a free-form surface

FIGURE 4.10 Automated premixed concrete panel placed on the digital flexible table in a single curved profile while curing

A major limitation of the digital flexible table with actuators and a surface membrane was the inability to make offsets in the surfaces (when compared to digital tables using pistons and a membrane), thus limiting the production of edge-returns and offsets for thin-wall GFRC panels (8).

A full list of the limitations of digital flexible table with actuators and a surface membrane are:

- Minimum 24 hour curing time of the concrete on the flexible table
- The inability to create offsets in the surface
- Accuracy (±2mm) of the table to meet the intended continuous surface
- Limited to radii of 0,5m and a maximum panel depth of 0,4m
- High cost of the table
- Limited durability of the membrane during multiple cycles.

The cost of the flexible table combined with the necessary 24 hour curing time for most fast curing concrete to avoid shrinkages cracks in the surface of the thin-walled GFRC panel (15) currently does not make flexible tables economically viable.

The limitations of existing flexible tables when producing a panel offset in the surface is difficult to replicate for large scale production because they can only be produce on the surface. So, for complex geometry thin-walled GFRC elements requiring an edge-return or an offset, flexible tables are not sufficient in themselves, however, utilising them as an intermediate step in the production of complex geometry thin-walled GFRC would potentially expand the capabilities of flexible tables.

§ 4.5 New moulding system for premixed GFRC

During the development of a new mould system it was important to understand the limitations and barriers imposed by existing systems. The main problem with mould systems using premixed GFRC with complex geometries is that they require a double sided mould to enable the concrete to flow into all parts of the mould. That mould also has to be vibrated to release trapped air-bubbles from the concrete mix. The main challenge in developing the mould system was to find a way to allow for an edge-return in the mould system. The edge-return is an essential aesthetic feature in contemporary architecture. On the Fundation Louis Vuitton in Paris (28) (22) this was solved by allowing a constant (60mm) panel thickness and to form the panels in their “greenstate” (43) using a vacuum system to ensure the concrete did not flow away from the corners. However, the system relied on ruled single curved geometries and was unsuitable for double curved surfaces with small radii and free-form surfaces.

The new mould system was intended for thin-walled GFRC produced with the premixed method that can utilize ultra-high performance concrete (UHPC). The new moulding system takes advantage of the flexible table with a continuous surface but introduces an intermediate step if an edge-return is required, allowing the flexible table to be used continuously to produce new moulds. Thereby utilizing the flexible table as a "mould-maker" to produce fast curing polyurethane moulds instead of curing the concrete directly on the flexible table which needs a minimum 24 hours curing time. This releases the flexible table for a mass production of moulds. It is proposed that the new moulds be made of fast curing self-expanding foam. The foam was intended to be two-component polyurethane that allowed for fast curing of the mould material to release the flexible table for making additional new moulds. Because the mould consisted of several layers of different density polyurethane it is possible to add the low density foam after the high density foam at a later workstation. A thin layer of approximately 1mm plastic polyurethane was applied on top of the high density polyurethane to allow for the mould to be reused and to assure the finished panel attained the required good surface quality.

Figure 4.11 illustrates the method to produce the positive mould for the new moulding system. The surface of the flexible table is highlighted in blue and the positive foam mould is indicated in yellow.

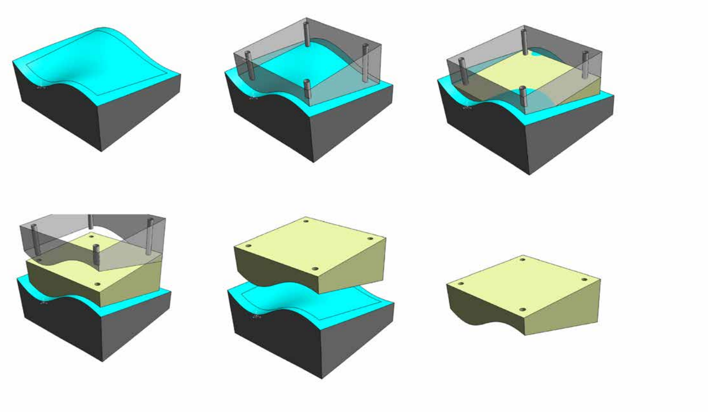

FIGURE 4.11 New mould system production of the negative mould

Figure 4.12 shows how the positive mould is produced. The green surface shows the repositioned surface of the flexible table. The black flexible band shown on the surface is used to create the offset in the negative mould surface. The blue part shows the negative mould with the offset.

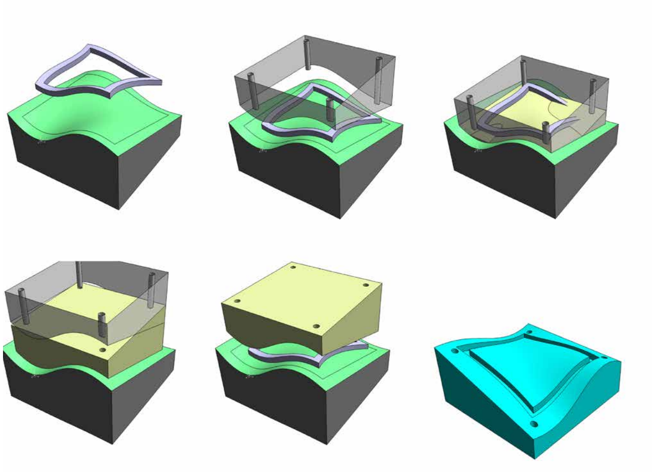

FIGURE 4.12 New mould system production of the positive mould

Figure 4.13 shows how the negative part from Figure 4.11 is assembled with the positive part from Figure 4.12. The black flexible band acts as a spacer and provides a void between the 2 mould elements.

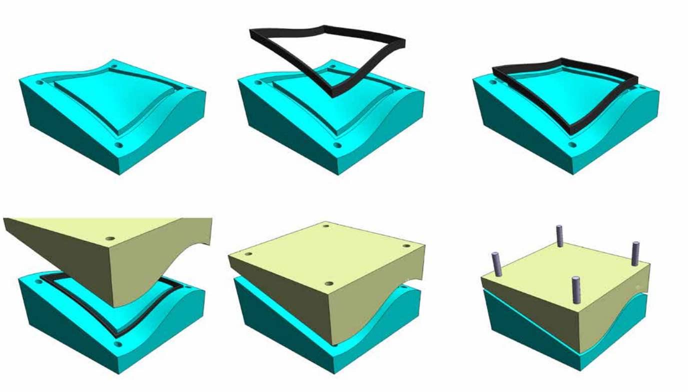

FIGURE 4.13 New mould system assembly of the positive and the negative mould parts

When the 2 parts are assembled it is possible to cast concrete between two elements, as shown in Figure 4.14 with the first prototype cast using the new mould system.

FIGURE 4.14 The first cast proto type utilizing the new mould system

The foam mould on the left represents the negative mould, and the foam mould on the right represents the positive mould. Figure 4.14 shows it was possible to create a continuous double curved surface with an edge-return using the new mould system.

This capability to create free-form thin-walled GFRC element with an edge-return is necessary to meet the demands of current architectural applications that require a visually desirable monolithic appearance.

The advantages of the proposed mould system are that it is cost effective and fast to manufacture compared with the other mould systems described in Table 4.1. The production speed using the foam casting technique allows the desired surfaces to be created in less than 5 min when compared to CNC milling of moulds, representing a significant reduction in production speed, and waste of materials.

The process also enables the production of recesses and holes in the surface, allowing complex shapes, which is not feasible with current moulding systems utilizing flexible tables. The top open mould has flexible sides, which are able to follow any curved shape while withstanding the pressure exerted by the casting and curing of the foam.

Table 4.2s shows the different types of mould systems and their limitations in relation to the complexity of the thin-walled GFRC elements, and the possibilities of the new moulding system.

PANEL GEOMETRY	EDGE DETAILING	MOULD SYSTEMS				
		Wooden moulds	Flexible table with pistons *	Flexible table with actuators and membrane **	CNC milled moulds ***	New mould system
Flat	Without edge-return	√	√	√	√	√
	With edge-return	√ (uniform thickness)	√ (Sprayed)	√ (Sprayed)	√	√
	With panel offset	√			√	√
Single Curved	Without edge-return	√	√ (large radii (R>0.5m))		√	√
	With edge-return	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√	√
	With panel offset				√	√
Double Curved	Without edge-return	√ (large radi-uses)	√	√	√	√
	With edge-return	√ (Sprayed)	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√	√
	With panel offset				√	√
Free form	Without edge-return		√	√	√	√
	With edge-return				√	√
	With panel offset				√	√

TABLE 4.2 The different types of mould systems and their limitations in relation to the complexity of the thin-walled GFRC elements, and the possibilities of the new moulding system.
* With the current developed piston tables it is not possible to get a continuous surface.
** Curing time reduces the usage of the flexible tables.
*** Surface quality of the CNC milled moulds is still problematic.

Existing moulding systems do not have the capability to meet current architectural aesthetic and design aspirations and the new process bridges this gap by offering a solution which meets the required surface quality with the option of having an edge-return with the same surface quality as the front surface.

§ 4.6 Process description

The new mould system is part of a process to achieve complex geometry GFRC panels with an edge-return without having to use CNC milled mould systems. With the process it is possible to manufacture thin-walled GFRC elements with the intended quality (15), in terms of surface quality and colour consistency, geometry and edge-return and panel offsets (8). The process differs from existing systems that only utilise flexible tables (44) because in additional to the complex shape it also allows for offsets and recesses which are paramount to create edge-returns.

The production of the foam mould for premixed GFRC is described as follow:

1. Generating a geometric shape using 3D CAD software, and subdivide the shape into single elements.
2. Positioning of the flexible table in the correct free-form position, using a predefined shape developed from 3D CAD software. (The first position creates the positive side of the finished foam mould).
3. Positioning of form-adaptable boundary walls to the flexible table
4. Positioning of silicone blocks to form the edge-return in the cast foam mould.
5. Casting of the foam inside the form adaptable boundary walls.
6. Curing of the positive side.
7. Repositioning of flexible table in the correct free-form position, using a predefined shape developed in 3D CAD software. (The second position creates the negative side of the finished foam mould).
8. Positioning of form-adaptable boundary walls on the flexible mould (Figure 4.15).
9. Positing of silicone blocks to form the edge-return in the cast foam mould.
10. Casting of the foam inside the form-adaptable boundary walls.
11. Curing of the negative side.
12. Assembly the positive foam mould side with the negative foam mould side.
13. Mixing the concrete in a vacuum mixer (45) to prevent air-bubbles.
14. Applying a release agent on the mould surface to allow for easy de-moulding.
15. Casting the premixed concrete in the finished foam mould using another vacuum system to remove any remaining air bubbles in the concrete.
16. Curing of the concrete for 28 days under controlled conditions.

With the flexible table it will be possible to cast unique free-form shape's foam moulds with the option of an edge return that can be used as moulds for GFRC panels. To allow the foam to be cast on the flexible table, a form-adaptable boundary wall equipment was developed.

FIGURE 4.15 Figure 37 form-adaptable boundary wall equipment, to be placed on the flexible table.

The method enables the production of moulds for GFRC, that is faster than current milling solutions. The mould also ensures that the concrete can cure for 28 days in a low-cost foam mould, enabling the flexible table to be used continuously in the production of foam moulds. Curing in the mould and under controlled conditions for 28 days allowed better control of the colour of the GFRC panel (46) (47). The new process permits the fabrication of complex geometry thin-walled GFRC elements using cost effective large scale production methods, for which a patent application was submitted in 2013 (48).

The cost of the new mould system is projected to be €250/m^2 however, this depends on the complexity of the edge-return and if a panel offset is necessary. Initial tests showed material costs of €190/m^2 excluding the labour costs and cost of using the flexible table and the equipment for spraying the polyurethane foam.

§ 4.7 Further advances

A new mould system and process for casting free-form GFRC elements has been developed for the premixed method. The method has been tested on smaller elements so the next step will be to upscale the size of the element and produce different geometries. The geometries that have been tested are double curved elements with an edge-return. Challenges still remain due to the non-recyclable nature of the foam mould material so future research will explore more sustainable alternatives.

To further advance the system it is necessary to find a solution to effectively produce moulds that can be combined with the sprayed method. The sprayed method would alone utilize a negative mould. This could ideally be made on the flexible table itself, however, issues with the side walls and the curing time on the flexible table have yet to be resolved. To create a foam mould from the flexible table it would be necessary to offset the main surface compared to the sides to create the edge-return. This would be possible on a flexible table with piston, however the piston technology has not been progressed sufficiently to meet the demands of a continuous surface. An automatic offset of the continuous surface has not been resolved with the current flexible tables and can currently only be solved by casting a foam mould on the flexible table.

To exploit the benefits of an automatic premixed method the new mould system would utilize the development of the new moulding system adapted to the sprayed method. The automated premixed method could be adapted to be utilized to follow the contours of a free-form surface, effectively allowing the GFRC to be "printed" on the surface of the free-form shape.

§ 4.8 Conclusion

Manufacture of free-form thin-walled GFRC element has been limited by current production techniques. This paper evaluates the key problems and limitations in the production of complex geometry thin-walled GFRC elements with panel offsets and edge-returns.

Existing moulding systems do not have the capability to meet current architectural aesthetic and design aspirations. The limitations of existing flexible tables when producing an offset in the surface is difficult to replicate for large scale production because currently the thin-walled GRFC can only be cast on the flexible table is selves. So, for complex geometry thin-walled GFRC elements, with an edge-return or a panel offset, flexible tables are not sufficient in themselves, however, utilising them as an intermediate step in the production of complex geometry thin-walled GFRC would potentially expand the capabilities of the flexible tables.

A new mould system to produce free-form thin-walled GFRC elements has been presented and can be used to replace CNC milled moulds for the manufacture of thin-walled GFRC. Such a system allows the mould for thin-walled GFRC element to be produced in a fast cost effective and more efficient manner. The projected cost for the new mould system is €250/m^2 this compared to similar system which are CNC milled double sided moulds is approximately a 50% reduction in the mould cost.

The new process described also permits the fabrication of complex geometry thin-walled GFRC elements using more cost effective large scale production methods. This offers a solution that bridges the gap between the limited capabilities of current solutions and the architectural aesthetic requirements of surface quality and the option of having an edge-return with the same surface quality as the front surface. A patent application for this innovative method of producing thin-walled GFRC was submitted in 2013 and granted in 2016.

Future research will examine the detailed integration of the proposed new mould system and process to the sprayed method and the fully automated methods to produce complex geometry thin-walled GFRC.

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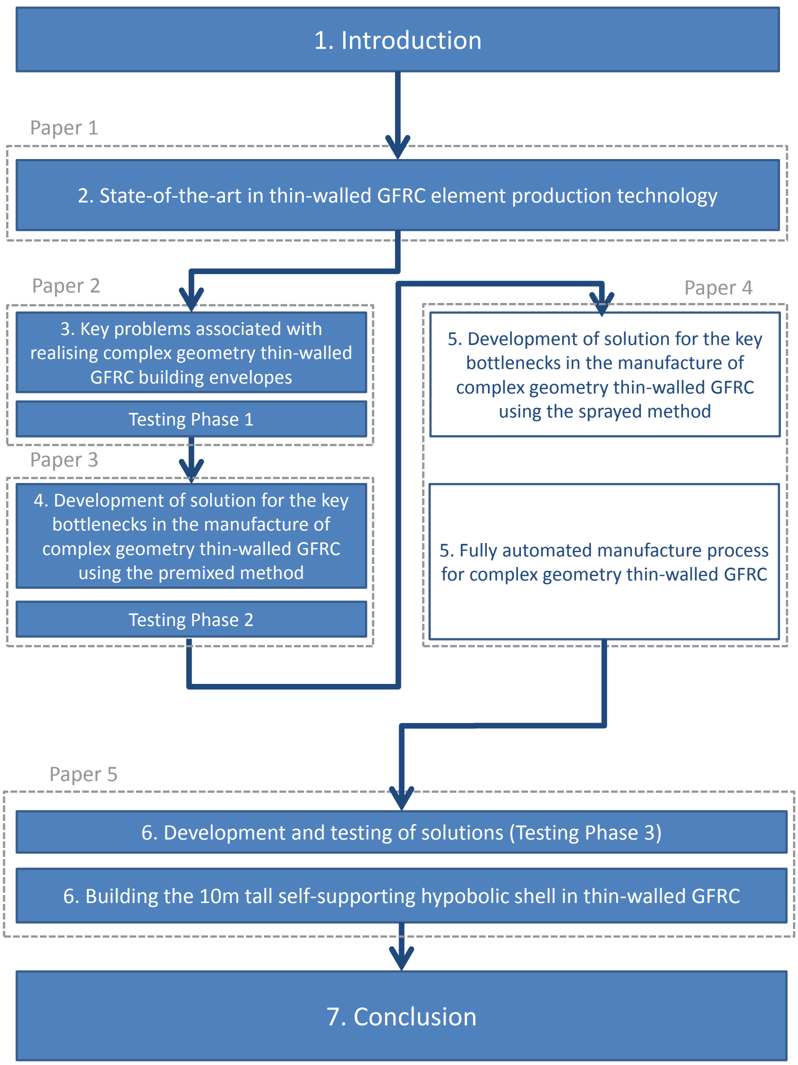
105 Developing a solution for the premixed concrete method and proposing a step by step fabrication process.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5 Developing a solution for the sprayed concrete method and proposing automated process.

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.

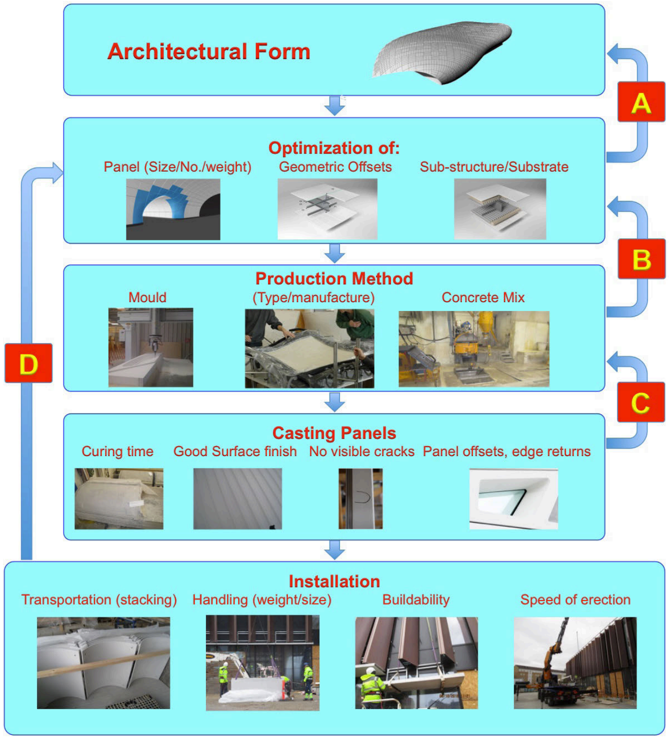
To advance the manufacturing stage of the design process a new mould system adapted to allow future "printed" GFRC fabrication has been developed and tested to assess it's suitability to the process. In addition, current mould materials based on non-recyclable foam materials were re-evaluated for their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

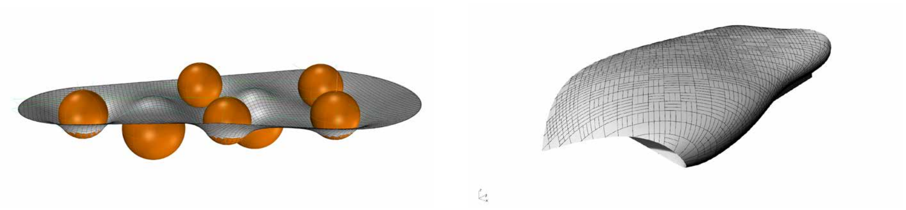


FIGURE 5.2 Initial generation of a free-form architectural shape and free-form architectural shape for a roof proposed to be built with GFRC

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

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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.

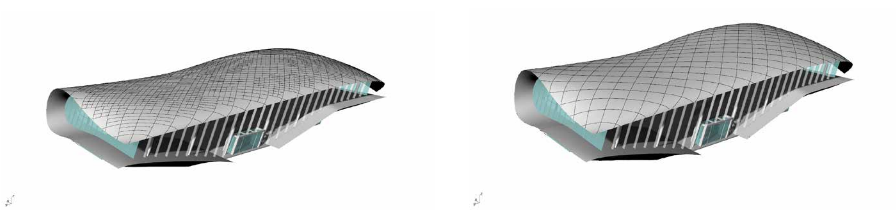

FIGURE 5.3 Visual consequences of panel size on architectural form

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.

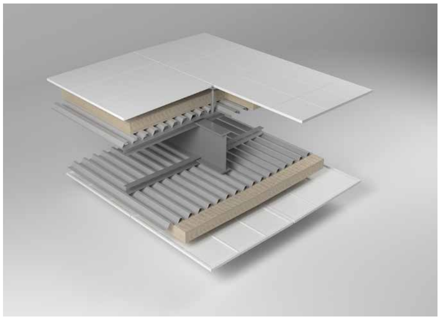

FIGURE 5.4 Geometric Offset

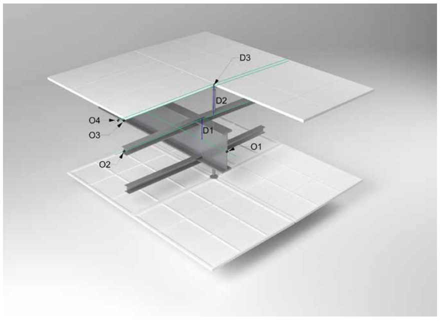

FIGURE 5.5 Geometric Offset with GFRC Panel in place.

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.

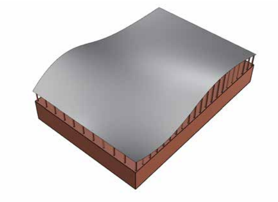

FIGURE 5.6 Positioning of flexible table.

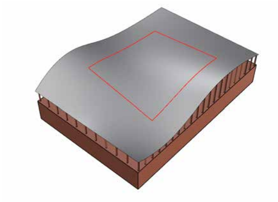

FIGURE 5.7 Outlining the boundaries of the panel on the flexible table.

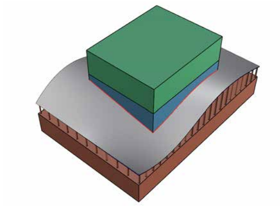

FIGURE 5.8 Casting the foam mould on the flexible table.

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.

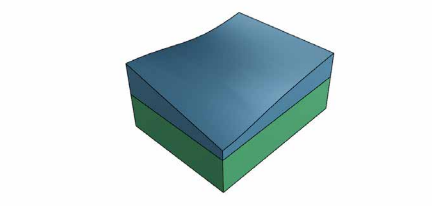

FIGURE 5.9 Finished mould.

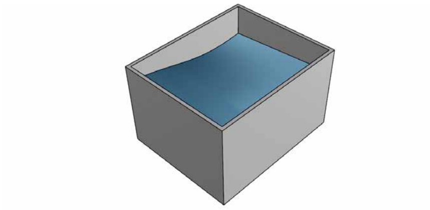

FIGURE 5.10 Side walls are added to the foam mould.

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.

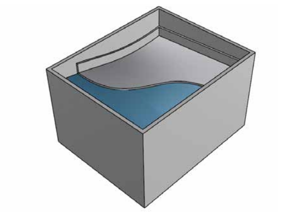

FIGURE 5.11 Sprayed concrete matrix is cast in the mould system.

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.

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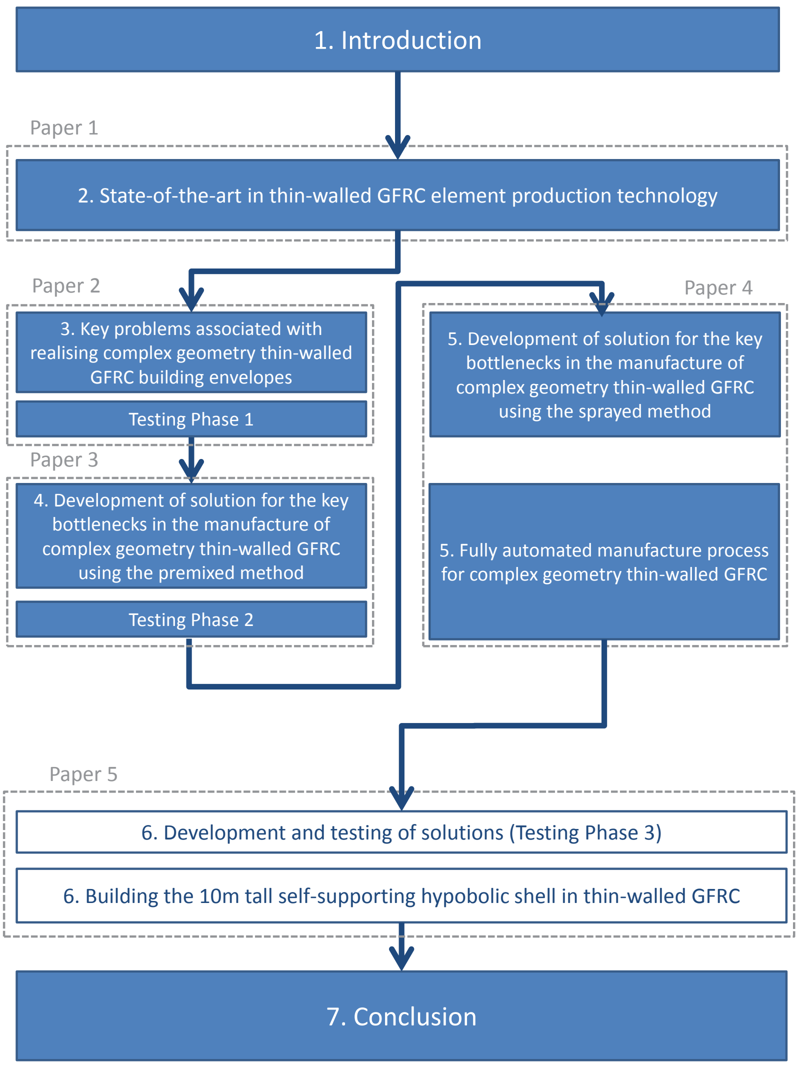
131 Developing a solution for the sprayed concrete method and proposing automated process.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Testing Phase 1
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7. Conclusion

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).

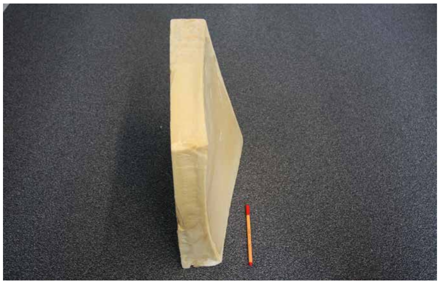

FIGURE 6.5 First sample of intermediate mould showing the double curvature of the mould, (40cm x 40cm).

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**).

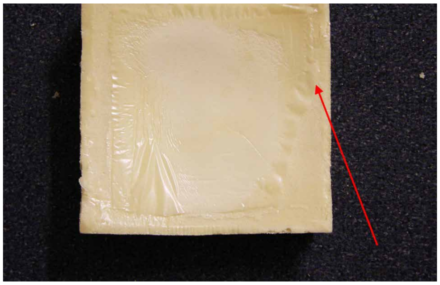

FIGURE 6.6 Intermediate mould with detached surface of LDPU foam, sample 23cm x 23cm

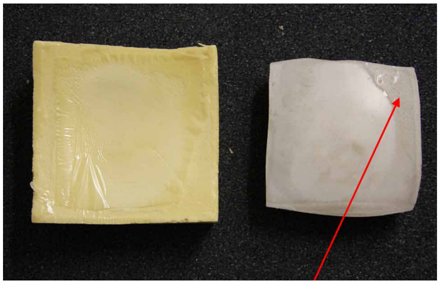

FIGURE 6.7 Premixed Concrete sample (18cm x 18cm) cast on the intermediate mould with marks from the detached surface of the LDPU foam, (23cm x 23cm)

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.

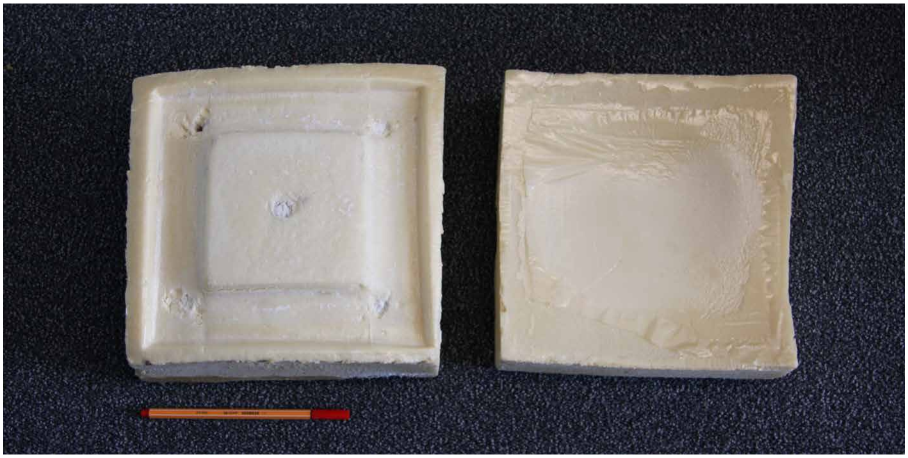

FIGURE 6.8 Small scale (23cm x 23cm) sample two-part intermediate mould for use with the premixed method.

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**).

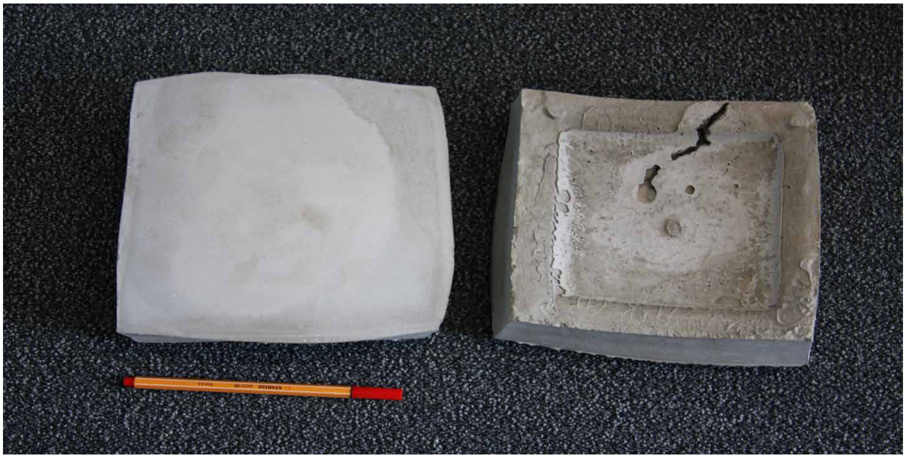

FIGURE 6.9 Premixed cast sample with small edge-return 18cm x 18cm. the challenge 2 and 3 in Table 6.1 are shown on the cast sample.

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

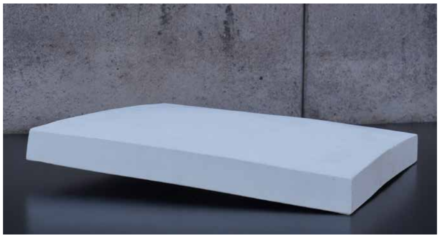

FIGURE 6.26 Finished double curved panel with a 40mm edge-return

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.

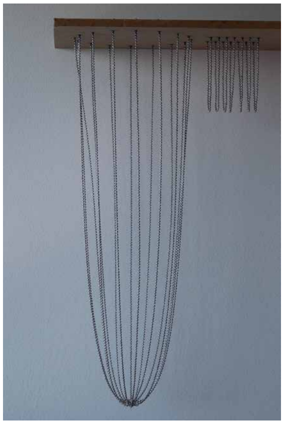

FIGURE 6.27 Catenary model of the initial design.

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

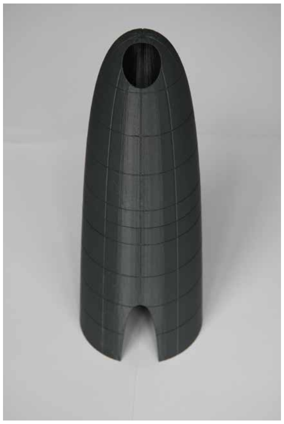

FIGURE 6.29 3D printed thermo-plastic model of the selected 1:500 scale hyperbolic shell.

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.

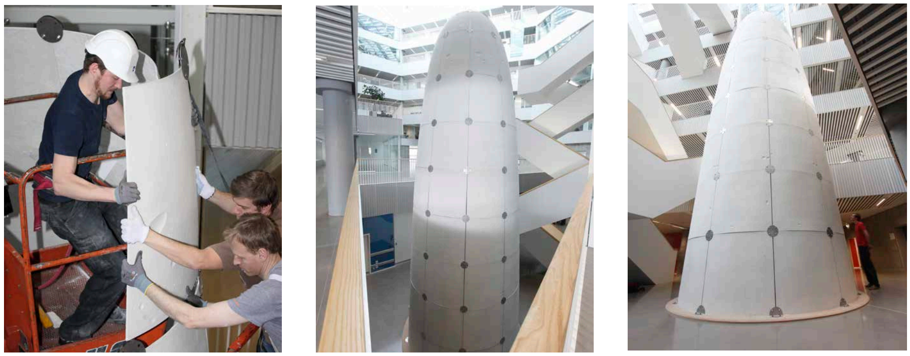

FIGURE 6.32 Panel installation and final self-supporting hyperbolic shell in-situ.

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.

§ 6.13 References

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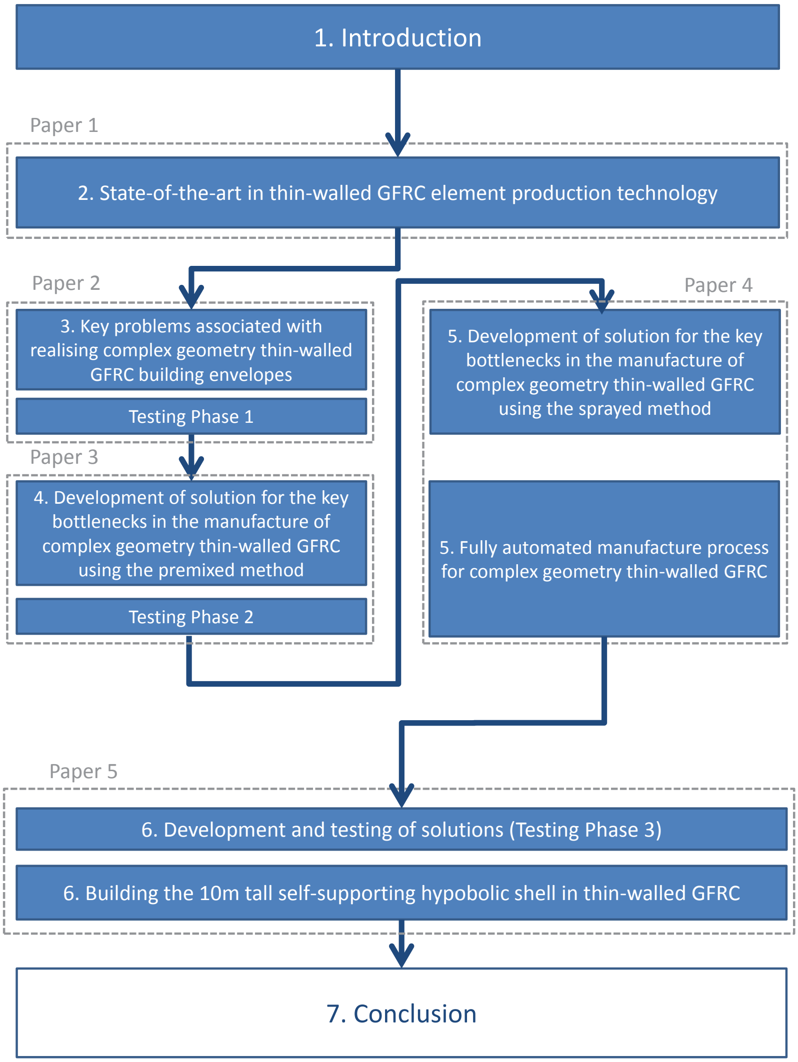
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7 Conclusion

§ 7.1 Introduction

The literature review for this research work has shown that there is a substantial body of research in the field of GFRC with a focus on its material behaviour. Advances and innovation in GFRC for application in the building industry was missing, so this work has advanced the material research considerably by taking the latest state-of-the-art material research and applying it to fabrication processes in the building industry and aligning it with today's architectural demands for complex geometry thin-walled GFRC.

Initial research identified state-of-the-art production technologies, and advantages and disadvantages were collated to identify the manufacturing method optimally suited to the production of complex geometry thin-walled GFRC panels.

The conclusions of this research work should enable designers to realise complex geometry building envelopes at a lower cost using thin-walled GFRC panels with the high degree of complexity demanded, while providing the industry with solutions that advance the processes of manufacturing thin-walled complex geometry GFRC.

§ 7.2 Answer to research questions

§ 7.2.1 Main research question

"How can the manufacture of complex geometry thin-walled GFRC be advanced to meet today's architectural demands?"

Thin-walled GFRC was developed in the 1970s for cladding applications when glass fibres were introduced as a material for reinforcement and its development as a cladding material was mostly in prestige architectural projects. Significant material development has been accomplished since the material was introduced as a decorative building envelop element in ornamental facades. To help advance thin-walled GFRC elements for complex geometry building envelopes in-depth research of the state-of-the-art application of thin-walled for complex geometry buildings has been undertaken. Defining the main demands for thin-walled GFRC as a cladding material was one of the key tasks, the demands established through interviews with leading specialist, designers and architects combined with visits to production plants and site visits. The demands were explained in chapter 3. The two main demands being, good surface quality and, an edge-return to ensure a monolithic appearance of the building envelope. For complex geometry thin-walled GFRC with an edge-return and, if necessary, a panel offset, the recommend production method was the sprayed method since this avoids voids in the surface, even when the panel shape had a complex free-form geometry with an edge-return. Using the premixed as an alternative method to produce these panels had difficulties avoiding voids and larger air-bubbles, with visible fibres in the surfaces proving difficult to eliminate. To manufacture a complex geometry thin-walled GFRC panel with an edge-return and a panel offset using the premixed method would require a precise two-part mould, and still it would be difficult to mitigate the voids and air-bubbles. The sprayed method uses a single-sided mould and by spraying a thin face coat, without fibres, ensured minimum air-bubbles and no visible glass fibres in the surface of the element. The advancement of complex geometry thin-walled GFRC elements for today's architectural demands has been restricted by the manufacture of the moulds used in the casting process. Following best practice guidance from leading manufacturers, this was identified in the initial tests with a flexible table at a production plant for automated premixed GFRC. As a result, a novel manufacturing method was proposed, initially for the premixed method because of the constraints of flexible tables, but eventually the sprayed method was adopted that successfully produced a complex geometry panel that met the demands of good surface quality with an edge-return. To test the viability of this novel method on a larger scale, a 10m tall self-supporting hyperbolic shell was manufactured and fabricated. The hyperbolic shell consisted of 95 double curved elements with the largest being 1,2m x 1,2m. To allow the shell to be built the panels did not have an edge-return but they all met the requirements of good surface quality. With the novel manufacturing method for complex geometry thin-walled GFRC elements it is possible to advance the current state-of-the-art production and meet the demands of today's architectural requirements.

§ 7.3 Answers to sub-questions

§ 7.3.1 Question 1

“What is the State-of-the-art in thin-walled GFRC element production technology?”

Many publications were produced in the 1960s and 1970s when GFRC was developed as a state-of-the-art building material with the first publication of production technology published in 1983. In the 1990’s and the 2000’s research in the field of GFRC concentrated on the material properties with fibres but little research focussed on production technologies. Visits to leading manufactures in Europe and interviews with leading manufacturers, engineering designers and architects was undertaken to establish the state-of-the-art in thin-walled element production technology. The objective of research sub-question 1 was to establish the optimal production technology most suited to the production of thin-walled GFRC elements, as a benchmark from where advances in their application could be made to achieve good surface quality while being able to create an edge-return. The criteria for a good surface quality were defined as:

1. Smooth texture of the surface
2. No visual fibres in the surface
3. Minimal air-bubbles or voids
4. Consistent colour across all thin-walled GRFC elements
5. No visible cracks

3 main production methods were identified; the premixed method, the sprayed method, and the automated premixed method. The automated premixed method is mainly used for flat sheets, and the 2 methods normally used for thin-walled GFRC elements, were the sprayed method and the premixed method. The sprayed method allows greater design flexibility for architectural thin-walled GFRC elements in terms of geometric complexity, when the back-side of the sprayed panels is not visible. The advantages and disadvantages of the sprayed method is shown in Table 7.1:

SPRAYED METHOD	
Advantages	**Disadvantages**
High fibre content	Labour intensive
Controlled fibre distribution	Quality dependent on skilled workmanship
Two-dimensional fibre orientation	Manual rollers have to be used to compact the fibres
Consistent surface quality	Low tensile capacity of sprayed concrete
No visual fibres in the surface	
High moment of rupture	
Complex shapes are possible	
Edge-returns are possible	
Reduced voids and air-bubbles	

TABLE 7.1 Advantages and disadvantages using the sprayed method for thin-walled GFRC elements.

With the premixed method glass fibre reinforced ultra-high performance concrete can be used. The advantage of the glass fibre reinforced ultra-high performance concrete is the increased tensile capacity. One of the main disadvantages of the premixed method is the high cost of the ultra-high performance concrete compared to typical sprayed GFRC, and because complex shapes usually requires a double sided mould compared to a single sided mould for the sprayed method. The advantages and disadvantages of the premixed method is shown in Table 7,2:

PREMIXED METHOD	
Advantages	**Disadvantages**
Ultra-high performance concrete can be used	Low fibre ratio
Self-compacting concrete can be used	3-dimensional fibre orientation
Mould can be vibrated	Fibre not uniformly distributed
Flat moulds with voids can be used	Flat moulds have to be used
Steel reinforcement can be added	Edge-return difficult to integrate
Less labour intensive	Consistent surface quality is difficult to achieve
	Voids and air bobbles are difficult to mitigate

TABLE 7.2 Advantages and disadvantages using the premixed method for thin-walled GFRC elements.

For applications requiring large areas of GFRC, a high number of different elements are needed, and where automated flat GFRC sheets cannot be used, the sprayed method shows the greatest potential, with the greatest flexibility. Therefore, this research showed that the 3 different production methods for thin-walled GFRC, namely the premixed method, the sprayed method, and the automated premixed method, represent the State-of-the-art. The premixed method and the automated premixed method can utilise ultra-high performance concrete, but are generally best suited for flat and simple geometries. The sprayed method was the most flexible method and had the greatest potential to advance thin-walled GFRC for more complex applications.

§ 7.3.2 Question 2

"What are the key problems associated with realising complex geometry thin-walled GFRC building envelopes?"

The key problems associated with realising complex geometry thin-walled building envelopes are twofold; the limitation of today's productions methods used for fabricating complex geometry thin-walled GFRC (the sprayed method, the premixed method and the automated premixed method), and, the manufacture of the moulds used by these 3 productions methods. These problems must also be resolved while trying to create a monolithic appearance and good surface quality of the building envelope. These were the main challenges to realising complex geometry thin-walled GFRC elements. To resolve these challenges initial research focussed only on rainscreen panels for thin-walled GFRC building envelopes, and initially disregarded integral walls and insulated walls. Once these challenges have been resolved it will be possible to expand the solutions to integral walls and insulated wall panels in future. An illustration of the key challenges of the research is highlighted in Figure 7.1.

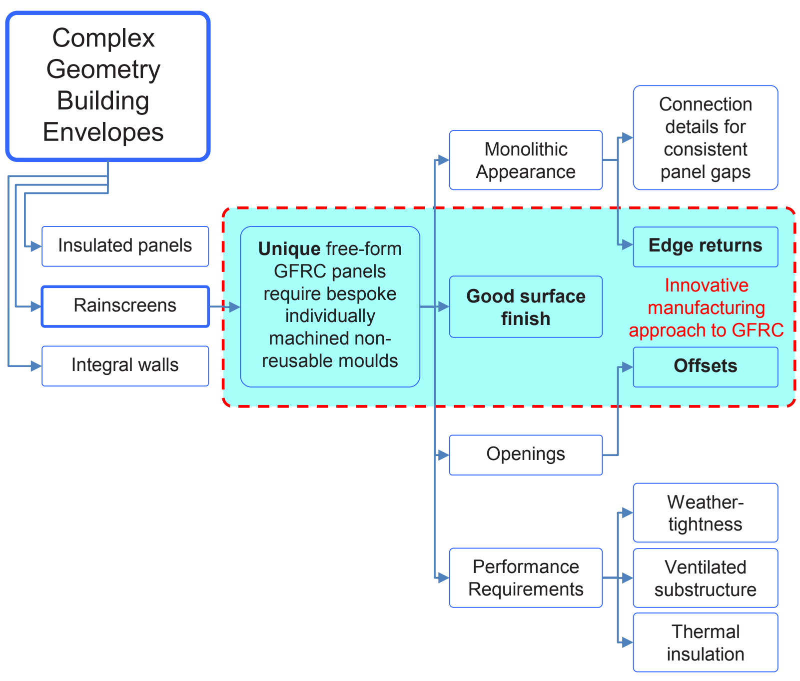


FIGURE 7.1 An innovative approach to the challenges of complex geomerty GFRC rainscreen cladding

The monolithic appearance of a building envelope requires the complex geometry panels to have an edge-return and for window openings a panel offset. Meeting the demand for good surface quality is difficult to realise for all the 3 production methods for complex geometries. For each method the possibilities and limitations were examined, and showed that the sprayed method offered most flexibility for complex geometry thin-walled GFRC elements. The automated premixed method was limited to flat and single curved elements and was difficult to make a continuous edge- return using this method. The premixed method has the advantages that it can utilise ultra-high performance concrete, however it was difficult to produce thin-walled GFRC panels in complex geometries with an edge-return without having to cast panels of a constant thickness to match the edge-return. For elements with small radii, or free-form panels with a panel offset, the premixed method was difficult to use, a vacuum bag solution could be used, however this would add additional complexity and would not completely mitigate the risk of air bubbles and voids remaining in the surface of the panel, which led to rejections. A comparison between the 3 methods is shown in Table 7.3.

PANEL GEOMETRY	EDGE DETAILING	PRODUCTION METHOD		
		Sprayed	Premixed	Automated pre-mixed
Flat	Without edge-return	√	√	√
	With edge-return	√	√	
	With panel offset	√	√	
	Folded panel	√		√
Single Curved	Without edge-return	√	√ (large radii)	√
	With edge-return	√	√ (uniform thickness)	*
	With panel offset	√		
Double Curved	Without edge-return	√	√ (large radii) †	*
	With edge-return	√	√ (large radii) †	
	With panel offset	√		
Free form	Without edge-return	√		*
	With edge-return	√		
	With panel offset	√		

TABLE 7.3 The limitations in GFRC production methods for the different geometric panels († Double curved premixed thin-walled panels with an edge-return are only possible in a double-sided mould. * Advances required in the automated premixed method to strive towards a fully digital complex geometry GFRC element process)

All 3 production methods were dependent on the mould in which the element was cast and for complex geometries the mould and the mould production is costly and time consuming, especially if all elements in a project are unique. An innovative approach to producing complex geometry moulds for casting thin-walled GFRC elements using a flexible table for custom made moulds to be produced was proposed, thus avoiding the need to mill the complex shaped moulds, making complex geometry thin-walled GFRC more cost effective. This approach added an intermediate step to use the flexible table as a “mould-maker” to allow the full benefits of a flexible table to be realised so that the cast mould could be used in the production of the full range of complex geometry GFRC elements. The key challenges are that the production technology for thin-walled GFRC has not followed the same development as 3D CAD software tools architects are using and the production of the moulds to cast the panels must rely on computer numeric controlled (CNC) machined milled moulds that are costly and time consuming to produce. Both challenges hinder advances in the manufacture and application of complex geometry thin-walled GFRC. Resolving these challenges will advance the architectural application of thin-walled GFRC in the future.

§ 7.3.3 Question 3

“What are the key bottlenecks in the manufacture of complex geometry thin-walled GFRC and how can they be resolved?”

The development of the fabrication methods for complex geometry thin-walled GFRC elements has not progressed as quickly as developments in 3D CAD software. This result in high fabrication cost of complex geometry panels and extended manufacturing times. The consequence is that the projects designed for complex geometry GFRC are rarely built, and the geometry is often simplified or the material skin is changed to a cheaper material e.g. glass fibre reinforced plastic (GFRP). The extended manufacturing times result from key bottlenecks during the fabrication of complex geometry thin-walled GFRC, namely the production of the moulds for the GFRC elements capable of allowing an edge-return while providing a good surface quality. Existing 3D CNC machined moulded solutions are limited by the complexity of the geometry, the long milling time necessary to create the intended shapes and the material waste. In addition, the quality of the milled surface of such solutions is dependent on the milling tool and requires post treatment to achieve the demanded surface quality. Finally, these 3D CNC machined moulds are costly and time consuming to produce. The development of flexible tables that can form complex geometry surfaces has advanced the technology in mould making. However, they are not suited to large scale production of thin-walled GFRC elements because of the long curing time needed on the table (24h). This was highlighted following initial testing of a flexible table with uncured thin-walled GFRC sheets from an automated premixed production line. So, an innovative approach was developed, that resulted in an intermediate step between the flexible table and the casting of the concrete using a new mould system based on fast curing foam. The intermediate step utilised the advantages of the flexible table but by using a fast curing material reduced the curing time on the table from 24h to 1h. This released the flexible table for multiple casting cycles of this new mould making system. To solve the problem of the edge-return a two-part mould system was developed that utilized premixed concrete. The new mould system was tested and it was shown that the flexible table could be used to produce the new mould as an intermediate step. A comparison between the new system and existing system is shown in Table 7.4

PANEL GEOMETRY	EDGE DETAILING	MOULD SYSTEMS				
		Wooden moulds	Flexible table with pistons *	Flexible table with actuators and membrane **	CNC milled moulds ***	New mould system
Flat	Without edge-return	√	√	√	√	√
	With edge-return	£ (uniform thickness)	£ (Sprayed)	£ (Sprayed)	√	√
	With panel offset	√			√	√
Single Curved	Without edge-return	√	√ (large radii (R>0.5m))		√	√
	With edge-re-turn	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√	√
	With panel offset				√	√
Double Curved	Without edge-return	√ (large radiuses)	√	√	√	√
	With edge-return	√ (Sprayed)	√ (uniform thickness, large radii)	√ (uniform thickness, large radii)	√	√
	With panel offset				√	√
Free form	Without edge-return		√	√	√	√
	With edge-return				√	√
	With panel offset				√	√

TABLE 7.4 The different types of mould systems and their limitations in relation to the complexity of the thin-walled GFRC elements, and the possibilities of the new moulding system.

* With the current developed piston tables it is not possible to get a continuous surface.

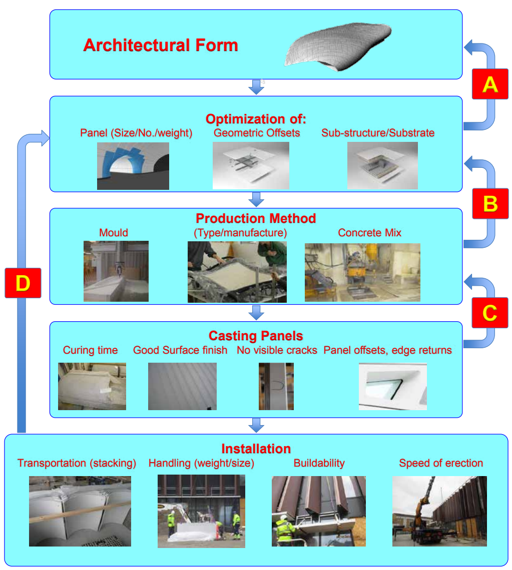
** Curing time reduces the usage of the flexible tables.

*** Surface quality of the CNC milled moulds is still problematic. It was also shown that it was possible to produce thin-walled GFRC panels with an edge-return and a good surface quality with this new mould system. The new mould system has been patented (Patent number WO2014138759 A1) and resolves the main bottleneck during the manufacture of complex geometry thin-walled GFRC.

§ 7.3.4 Question 4

"How can the solution to the bottleneck be integrated into a fully automated manufacture process for complex geometry thin-walled GFRC?"

Advancing the adoption of complex geometry thin-walled GFRC requires a more automated and fully digital manufacturing process to be developed. Current manufacturing processes are disengaged from the initial design process that has consequences for the development of projects that specify complex geometry GFRC. If an inappropriate manufacturing method is chosen, this can lead to the originally specified GFRC being replaced with other materials that are easier to handle in the manufacturing process, e.g. GFRP. The process with feedback loops are shown in Figure 7.2.



	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 7.2 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.

A fully automated GFRC manufacturing process can be developed by introducing plug-ins pre-loaded with embedded manufacturing restraints and barriers. This would allow the conceptual geometric form of the buildings to be developed during the early stages of the design, while taking into account constraints that normally arise later in the design and fabrication process. The key barriers to a fully automated and digital process for complex geometry GFRC, and how they can be resolved is outlined in Table 7.5

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 7.5 Barriers and proposed solutions for a fully automated and digital process.

The plug-ins would also embed constraints from each different manufacturing method as described in chapter 3. The development of the plug-ins are outside the scope of this research but their solution will advance complex geometry thin-walled GFRC. To progress the current manufacturing process towards a fully automated process for complex geometry thin-walled GFRC it is also necessary to resolved the main bottleneck, namely the production of complex geometry moulds. The new two-part mould system proposed (described in chapter 4) is difficult to adapt to a fully automated manufacturing process when using the premixed method, whereas a fully automated process is more viable using the sprayed method. When fully developed the sprayed method of applying GFRC would be similar to "printing" the GFRC onto the complex geometry moulds. To utilize the new mould system originally developed for the premixed method it was necessary to adapt the mould system for the sprayed method by going from a two-part mould system to a single sided mould system. The challenge with the single sided mould system was creating an edge-return. The two-part mould system solves this by casting the negative mould side with an up-stand on the surface of the flexible table. To do the opposite and create a down-stand on the flexible table is currently not possible while also maintaining a continuous good surface. The initial solution to the problem was to cast the one-sided mould part on the flexible table and add an edge-wall around the edge of the mould to create an up-stand which the edge-return can be cast against. However, this solution restricted it to a projected edge-return and not an edge-return that was geometrically normal to the complex geometry surface. The adapted mould system allowed the sprayed method to be utilized so it could be integrated into a fully automated manufacturing process. This together with a development of plug-ins for 3D CAD software would advance complex geometry thin-walled GFRC. The integration of the fully automated process with the new adaptation of the mould system resulted in a novel manufacturing process.

§ 7.3.5 Question 5

"How can the resulting novel manufacturing method for complex geometry thin-walled GFRC be developed and tested?"

To advance complex geometry thin-walled GFRC it is necessary to test any newly developed methods for manufacture of the panels. The new developments were tested and the resultant challenges arising from them were identified and resolved. These challenges and their associated solutions are shown in Figure 7.3.

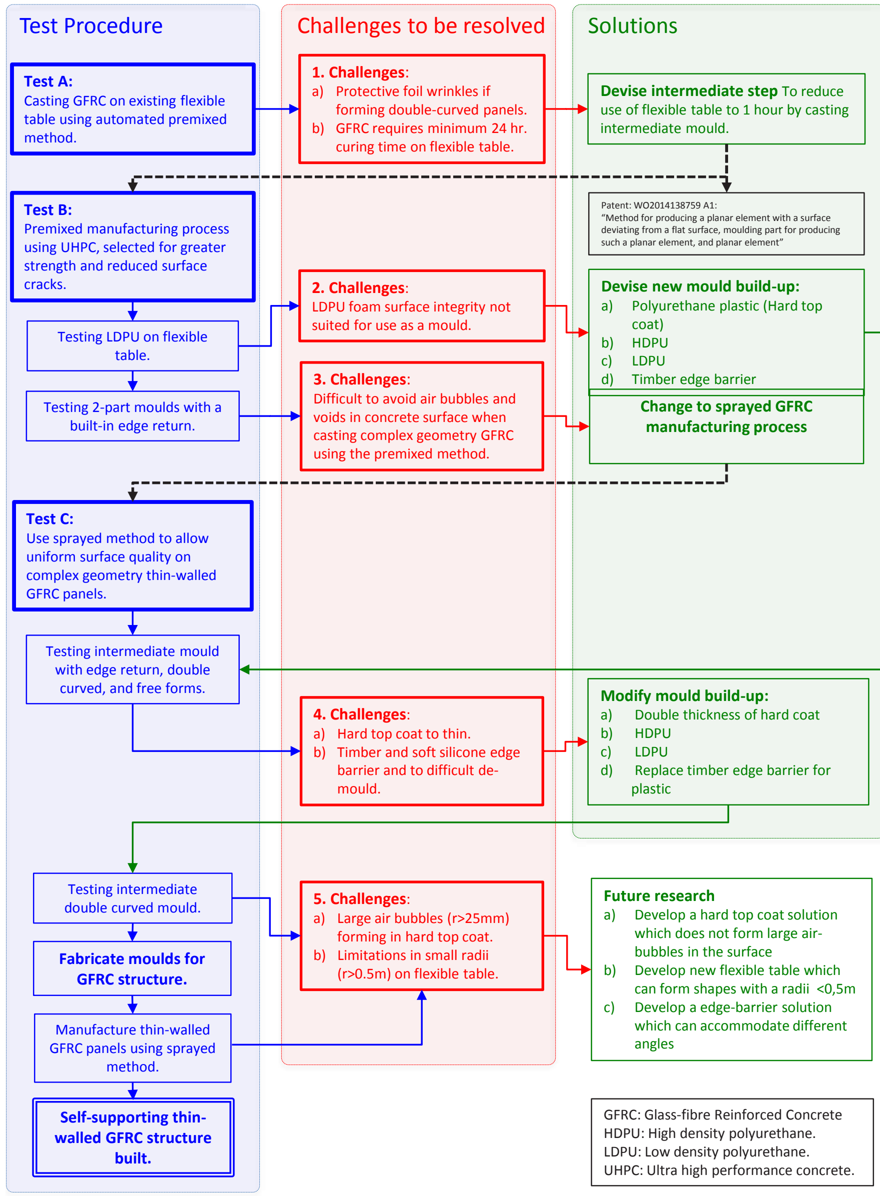


FIGURE 7.3 Development of experimental procedure for thin-walled GFRC panels

In the beginning of the research phase a flexible table was tested for its suitability for producing complex geometry thin-walled GFRC panels. This was undertaken at a production plant for automated premixed thin-walled GFRC by transferring a newly produced flat GFRC sheet in its "green-state" onto the table and then adjusting the table into its pre-programmed geometric shape. The sheet was then cured for 24hrs at a temperature (40 °C) in a humidity controlled environment (between 90-100%) on the flexible table. The outcome of the initial test showed that for the current automated premixed GFRC sheets it was only possible to form them into single-curved geometric shapes. Double-curved or free-form shapes resulted in fold lines appearing in the GFRC sheet. The second conclusion from the test was that the flexible table was not suitable for larger scale projects because of the long curing time needed on the flexible table. So an intermediate step was introduced that cast faster-curing low-density polyurethane on the surface of the table, thus using it as a mould-maker. This achieved the desired outcome by having a good surface quality, one of the key demands mentioned in sub-question 3. The development of this novel manufacturing method also needed to address the additional demand of having an edge-return in the complex geometry GFRC element. The challenge with the edge-return was initially solved by having a two-part mould where the edge-return would be set in the negative part of the mould, and produced by adding a square quadratic silicone band on the flexible table and then casting the negative mould. The two-part mould system was tested successfully on smaller samples using the premixed production method. It was possible to produce a sample with an edge-return and good surface quality on the sides and on the top of the complex geometry GFRC element. However the low-density polyurethane did reveal disadvantages in terms of the durability of the crust of the new mould surface. At the same time it was evident that it was difficult with the premixed method to avoid air-bubbles and voids forming inside the two-part mould. The new single-sided mould system was successfully tested to produce 1,2m x 1,2m double curved samples with a good surface quality, but without an edge-return. Initially different materials were evaluated as an edge-barrier, and for creating a panel without an edge-return a 10mm x 10mm PTFE strip was used. However the PTFE was difficult to use if an edge-return > 30mm was required, since it was difficult to bend a 30mm x 30mm PTFE strip to fit to the changing surface geometry of the single sided mould system. To resolve the problem, hard silicone was cast directly on the single sided mould to form an edge-return. A 0.5m x 0.5m test mould was made with the 50mm high hard silicon as an edge-barrier. The test mould was used with the sprayed method then cured, and finally demoulded. The result was a thin-walled double curved panel with a 50mm edge-return. The demands for good surface quality on both the surface of the panel and the edge-return had been fulfilled. The test mould and the new panel are shown in Figure 7.4 and 7.5.

FIGURE 7.4 Intermediate mould with high edge-return

FIGURE 7.5 Finished double curved panel with a 40mm edge-return

This panel showcased that it was possible to produce a complex geometry thin-walled panel with good surface quality while achieving a monolithic appearance with edge-returns.

§ 7.4 Limitations to this research

§ 7.4.1 Limitations in research field

The main focus of this research have been rainscreen envelopes, explicitly exterior thin-walled GFRC for complex geometry cladding panels, that do not have any weather and water-tightness performance requirements, disregarding insulated GFRC panels and integral walls. The focus has mainly been on the aesthetic demands of complex geometry thin-walled GFRC elements, and not the material behaviour of thin-walled GFRC. The research has been undertaken predominantly using the European state-of-the-art knowledge base for thin-walled GFRC with visits to manufactures in Europe and the Middle-east. Interviews with manufacturers in the Far East (China and India) and the Americas have been made at conferences, but it has not been possible to visit the Far East and American based manufactures. Based on the interviews is has been assumed that the knowledge-base in the Far East and the Americas are similar to the European knowledge-base. This assumption was based on information from interviews and review of literature.

§ 7.4.2 Definition of aesthetic demands

Little literature addresses the aesthetic demands of concrete panels, in particular, research that defines good surface quality and how to control colour consistency from different batches of concrete mixes when cured. The existing knowledge base has been taken from industry guidelines from PCI and GRCA and the CEN/TR 15739. The term "good surface quality" has not been defined explicitly in this research, however it is assumed to be a surface with a minimum number of flaws visible to the naked eye. The minimum requirement which is typically being specified for GFRC panel for complex geometry projects are 10 flaws per panel as long as they are not in a cluster or are bigger than 3mm by 3 mm. The same applies for the term "colour consistency" and visible cracks as defined in chapter 2, assumed to be cracks that are visible by the naked eye, normally a crack width larger than 0.1mm.

§ 7.4.3 Test limitations

All laboratory tests were undertaken using a flexible table developed by Aalborg University in 2009 with the current maximum table size limited to 1.2m x 1.2m and the accuracy in matching the ideal spline curve being ±2mm. The minimum radius the table can accommodate is 0.5m. Therefore all tests were made within these constraints. The developed novel manufacturing system is dependent on a flexible table to digitally make the complex geometry shapes used for casting the polyurethane based mould system.

§ 7.5 Conclusions

The manufacturing processes for thin-walled GFRC elements were evaluated based on a review of the literature, visits to leading European manufacturers, interviews with key designers, architects, building case studies and tests performed in process specific laboratories. The study identified 3 main manufacturing methods that could be used to manufacture complex geometry thin-walled GFRC elements, the results are discussed for each method and design recommendations made. The study also identified a novel manufacturing method that enables more complex geometry GFRC panels to be produced at a lower cost.

§ 7.5.1 Premixed method

The premixed method is used by many manufacturers because it can utilise ultra high performance concrete. The surface quality that can be achieved with the premixed method is comparable to the sprayed method. However, it depends on using an open-sided mould that must be vibrated to remove air-bubbles trapped in the concrete mix. However, the method is restricted to flat geometries or geometries with large radii. Casting an edge-return around the panel requires a two-part mould system at increased cost compared to a single sided mould. The alternative is to have constant thickness panels to match the edge-return resulting in a higher panel weight and greater material usage. Initially the intermediate step to produce a new mould system was developed for the premixed method, because of the ability to easily cast the negative part of the mould with the recess for the edge-return on a flexible table. However, this initial test identified problems with voids and air-bubbles in the cast thin-walled GFRC samples. Such problems could only be solved by using a vacuum bag to ensure that all the concrete reaches all parts of the mould. Unfortunately, the vacuum bag does not mitigate the problem of air-bubbles and vibrating a complex geometry shaped mould is not easy. It is possible to produce high-end two-part moulds but was not deemed possible with the new mould system developed for the premixed method. The cost of the novel manufacturing process for premixed GFRC would be considerably higher compared to a similar process using the sprayed method. It was concluded that the premixed method was not the best method for the manufacture of complex geometry thin-walled GFRC elements so no further tests with the premixed method were conducted.

§ 7.5.2 Sprayed method

The sprayed method is the main alternative to the premixed method and was developed alongside the development of the GFRC. This method is labour intensive and requires skilled workmanship to achieve constant high quality of thin-walled GFRC panels. However, the sprayed method gives the most flexibility in terms of producing complex geometry thin-walled GFRC elements. With the sprayed method it is possible to manufacture a complex geometry thin-walled GFRC element with a good surface quality and an edge-return that meets the requirements for a monolithic appearance. One of the limitations of the sprayed method is the back-side of the sprayed panel cannot achieve a similar surface quality to the front. The challenge with advancing complex geometry thin-walled GFRC using the sprayed method was adapting the new mould system, originally developed for the premixed method, so it could be used for the sprayed method, because the sprayed method only required single sided moulds.

The main problem arose from the flexible table when having to create a single sided mould with a raised edge. The flexible table is unable to make steps in the surface of the table when the complex geometry shapes are generated. The initial solution to the problem was to locate side walls on the edge of the new mould as shown in chapter 5, with the limitation of the edge-return being projected from the surface of the thin-walled GFRC panel. To advance the initial solution further a test mould was made using silicone with a high shore hardness as the raised edge cured directly on the new mould system. The test mould with a silicone raised edge, with shore 80, was successfully tested with the sprayed method. The sprayed method together with the novel manufacturing method can be used to advance complex geometry thin-walled GFRC.

§ 7.5.3 Automated premixed method

The automated premixed method is currently the most cost and time efficient method of producing thin-walled GFRC. It allows fibre meshes to be integrated into the elements automatically, and the process can be fully computer controlled from the initial mixing of the pigment colours used in the concrete, to controlling of the thickness of the panels. The method can utilize both ordinary portland concrete and ultra high performance concrete. The method allows a large output of flat thin-walled sheets compared to the other methods. The necessity to use foils to ensure a good surface quality limits its use to single curved geometries. It is not possible to cast custom made edge-returns without folding the edges of the GFRC sheets in their "greenstate". However, the edge-return would in this case need a mechanical fixing to support the GFRC against breakages. Based on this research the automated premixed method could be adapted to include an intermediate step, to produce a new mould system for the sprayed method. The GFRC could then be cast directly on the bespoke complex geometry moulds instead of the flat sheets. This would enable a fully digital and automated manufacturing method for complex geometry thin-walled GFRC.

§ 7.6 Novel manufacturing method

The proposed novel manufacturing method is one of the main findings of the research. The method introduces an intermediate step between the flexible table and current mould systems, using a fast curing foam material. The novel method was identified when testing a flexible table with the automated premixed method. From this test it became apparent that the flexible table alone would not meet the requirements for a rapid production process because the concrete elements required a curing period of 24h on the flexible table for that period. The novel method utilizes the flexible table more effectually by using the flexible table to cast fast curing moulds (in < 1hr) that in turn, could be used for casting the complex geometry GFRC panels. This novel two-part manufacturing method was used to produce 95 thin-walled double-curved GFRC panels to fabricate a 10m tall thin-wall GFRC tower in 9 days compared to 95 days if casting GFRC directly onto one flexible table.

The intermediate step of this two-part process fulfils the key requirements set out in the research by increasing the manufacturing speed of bespoke complex geometry thin-walled GFRC at a significantly reduced cost. This would result in more complex geometry building envelopes being built by reducing the risk of existing thin-walled GFRC being value engineered out of the project, or replaced by GFRP, due to their high cost.

This research sought to reduce the manufacturing cost of double curved and free-form panels with the development of the novel manufacturing system.

This research has also confirmed that the sprayed method was the most appropriate manufacturing method for complex geometry thin-walled GFRC building envelopes. For large panels (typically 1m x 2m) where the thin-walled panels require reinforcement it is recommended that a stud frame is embedded into the thin-walled panel. The fixings between the thin-walled GFRC panels are the main structure of the build and should be secured via the stud frame to avoid fixings through the GFRC on site.

§ 7.7 Design recommendations

This research will benefit designers, architects and manufacturers, by advancing the state-of-the art, allowing more complex geometry thin-walled GFRC building envelopes to be realised.

The design recommendations from this research will encompass the architectural and engineering sectors; material technology, structural engineering, architectural technology, mathematical geometry, design-, manufacturing- and project execution-processes.

Recommendations for flat thin-walled GFRC panels with an edge-return and panel offset is shown in Figure 7.6.

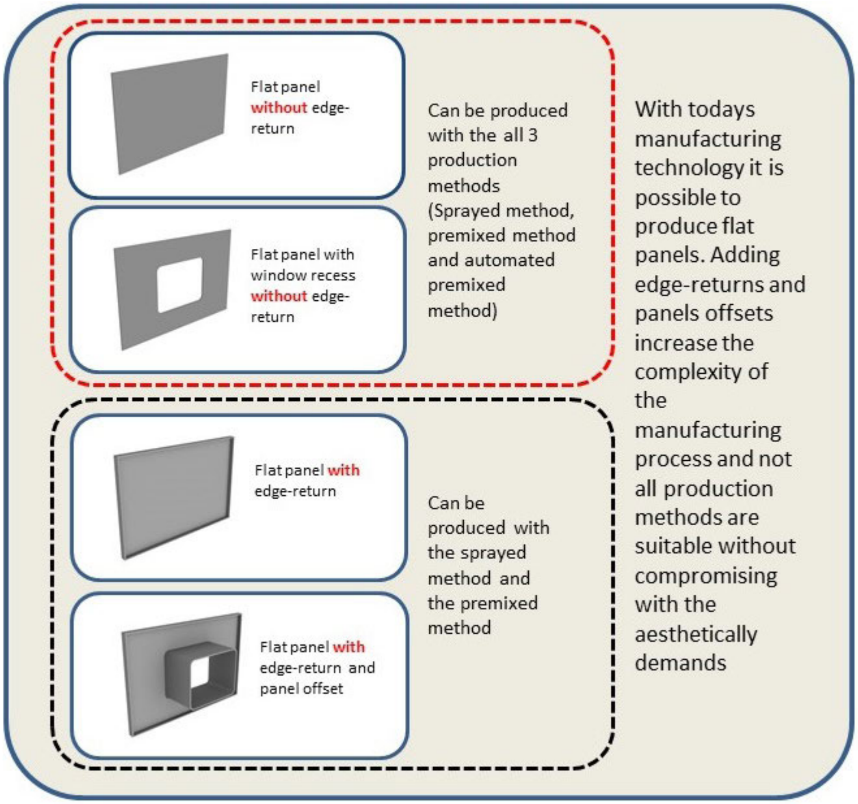


FIGURE 7.6 Recommendations for flat thin-walled GFRC panels with an edge-return and panel offset

Designing successfully with complex geometry thin-walled GFRC requires a detailed understanding of the limitations and barriers from early conceptual design to the installation. This is because todays manufacturing technology for thin-wall GFRC has restrictions that limit the production of all shapes and sizes.

Recommendations for single and double curved thin-walled GFRC panels with an edge-return and panel offset is shown in Figure 7.7.

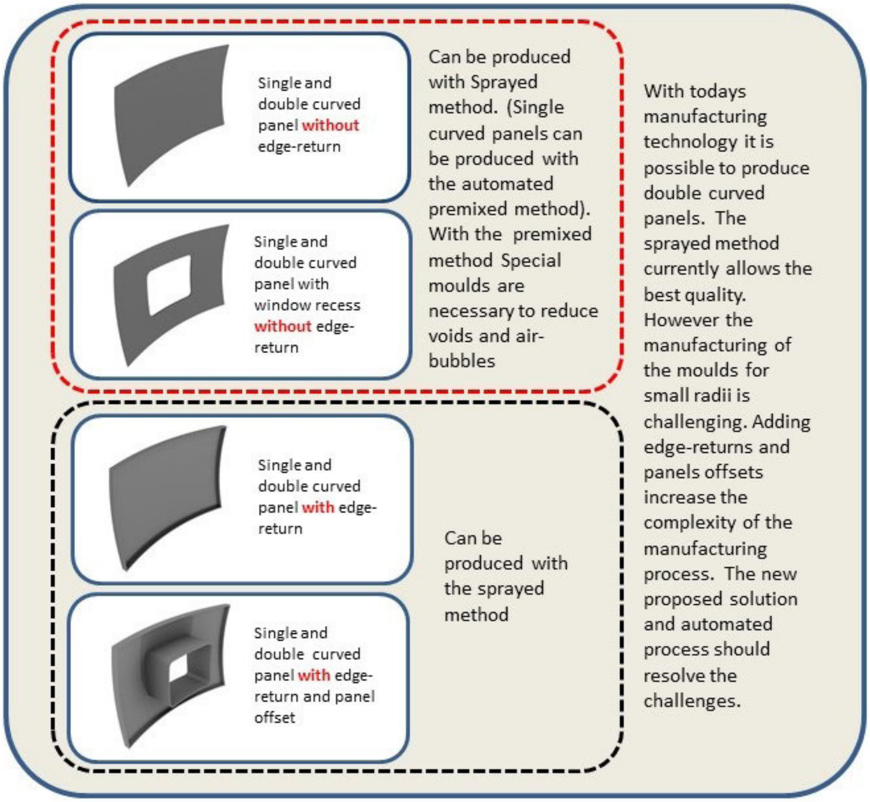


FIGURE 7.7 Recommendations for single and double curved thin-walled GFRC panels with an edge-return and panel offset

§ 7.7.1 Maximum sizes

The maximum sizes of panels can be divided into two categories, panels with and without an integrated sub-structure. For panels without an integrated sub-structure the restrictions to size are the mechanical properties of the GFRC being dependent on the span, thickness and the tensile capacity of the panel, and the ultimate load applied to the panel. Panel sizes larger than 2m x 2m normally would need an additional rib structure that increases weight, making the panels difficult to handle, transport and install. For ease of handling and installation, panels weights should be kept under approximately 50 kg so they can be handled by 2 people (assuming one person is allowed to lift 25kg without installation machinery). The size of panels with an integrated sub-structure are limited by the volume of each batch of mixed GFRC to ensure each panel can be cast using the same batch. Panel sizes larger then 3m x 3m require special means of transportation and on-site installation equipment due to their increased weight. In the development of the initial conceptual geometry the focus considered the sizes of the panels and any planned panel offsets or edge-returns. An appropriate manufacturing method should be selected early in the design process that matches the requirements of the most complex panels in the design. The charts and tables in chapter 3 and in chapter 5 were devised as guidance to enable the appropriate manufacturing method to be selected while understanding the limitations of GFRC throughout the building process.

§ 7.7.2 Curvature restraints

The curvature restraints of the panel can be categorised into 3 groups:

1. Curvatures with a radius smaller than 0.5m,
2. Radii between 0.5m and 8-10m, and,
3. Curvatures with a radius above 10m which can be produced with simple mould systems.

The constraints on the curvature of thin-walled GFRC panels are different dependent on the fabrication method, where not all methods are viable for curvatures with a radius smaller than 0.5m. The mould production method also has an influence. With wooden moulds it is difficult to curve the wooden surface without breaking the wooden fibres. The flexible table used in this research is limited to curvatures larger than 0.5m because of the distance between the actuators and the elongation length of the piston in the actuator. Moulds for panels with small radii can be produced by carving them out of solid material or by milling them with a 3D CNC milling machine, this requires the surfaces to be smoothed before the GFRC is cast on the moulds. However, the majority of panels used for complex geometry buildings are normally in the middle category of curvature, with radii between 0.5 m and 10m. Within this range it is possible to utilize flexible tables with the new mould system developed as part of this research. The current constraints is illustrated in Figure 7.6.

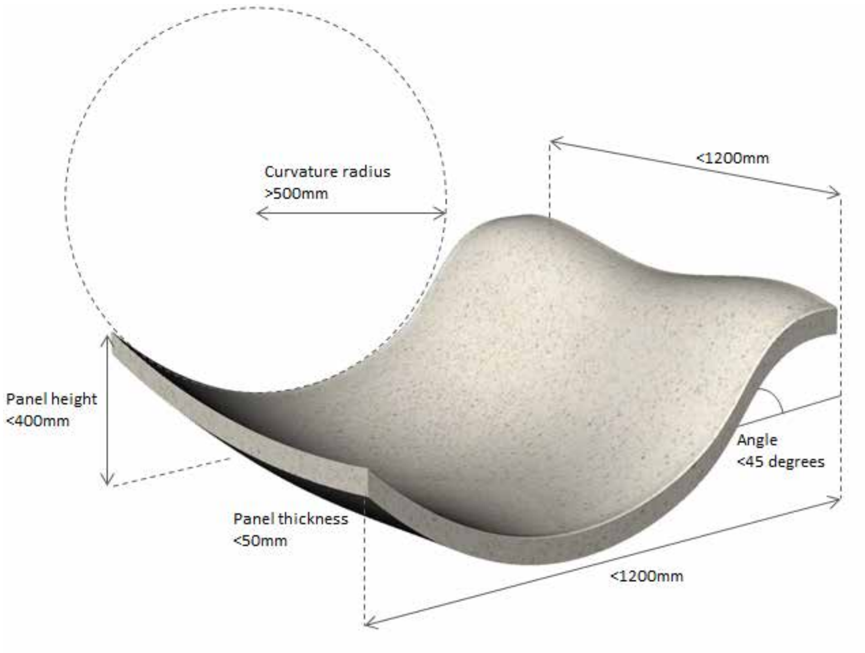


FIGURE 7.8 Limitations in flexible table used in this research

With a maximum tested size of the flexible table up to 1.2m x 1.2m, a minimum radius of 0.5m with a tolerance of the curvature of approximately ±2mm and a maximum panel height of 0.4m. It is possible to make a larger flexible table but the scaling effect of a new table must be tested. To reduce the tolerances in curvature more actuators are necessary, significantly increasing the cost of each flexible table.

§ 7.7.3 Prefabricated double curved shell structures

This research demonstrates that it is possible to prefabricate double curved shell elements. The new mould system would allow the elements to be fabricated in a factory and transported to site for easy assembly. To allow for double curved shell structures which do not follow hyperbolic shape, as the tower in this research or where a double shell system can be used, similar to the dome of the Pantheon in Rome, Italy. This could be done by utilizing the sprayed method to manufacture the inner and outer panel of a double shell structure. With the sprayed system the visible inner and outer surfaces would meet the demands of a good surface quality. To enable the double curved shell structure to transfer shear forces between the inner and outer shell it is necessary to cast shear reinforcement into the inner and outer shell panel and mechanically connect the shear reinforcement. Within the cavity between the inner and outer shell, poly-urethane can be added to insulate the double shell structure. Similar solutions have been researched and tested for flat panels and can be developed to suit the double curved shell structure. Adding panel offsets as described in chapter 2 would allow openings to be added to the shell structure. The different proposed element types for structural discretised shells are shown in Figure 7.9.

	Single double curved shell element	Section of double curved shell structure
Discretised single shell structure		
Discretised double shell structure with shear reinforcement		
Discretised double shell structure with shear reinforcement and insulation		
Discretised double shell structure with shear reinforcement, insulation, edge-return and panel offset		

FIGURE 7.9 Proposed element types for discretised shell structures

§ 7.7.4 Free-form shell structures

With a similar technology used for double curved shells it should be possible to develop the new technology to allow for the construction of a free-form curved shell. The free-form shell differs from the double curved shell by having both positive and negative Gaussian curves in the same panel. This creates bending moments in the shells structure itself. These could be accommodated by varying the distance between the inner and outer shell, and using thicker material locally as required. The manufacturing complexity of a free-form shell is naturally higher than less complex double curved shell structures. Free-form shells can also have the same insulation between the inner and outer concrete shell and panel offsets for openings in areas without internal shell bending.

§ 7.7.5 Estimated cost of complex geometry GFRC

Under-estimating the cost of complex geometry thin-walled GFRC when used as rainscreen panels is often one of the reasons that complex geometry GFRC building envelopes are often realised with an alternative material. As part of this research the costs for the manufacture of the GFRC panels were collated and based on prices in Europe in spring 2016 but are only indicative manufacturing costs without any sub-structure. Estimated cost for panels:

- Flat panels: €100-150/m^2
- Single curved panels: €200-350/m^2
- Double curved panels (Radii > 3m): €450-550/m^2
- Double curved panels(Radii < 3m) €600-800/m^2
- Free-form panels: €600-1000/m^2

The estimated costs is not shown as part of the main research, however, the information has been collated from experience through bidding and working on building projects with complex geometry GFRC cladding from 2010 – 2016. Since the information may be used to estimate budgets in the conceptual stages of the design, and that similar information is limited it has been decided to include the indicative prices in the conclusion.

§ 7.8 Recommendations

§ 7.8.1 Recommendations for future research

This research work recommends four main areas for future research.

A Development of the sprayed method.
Future research should seek to develop the sprayed method to enable ultra high performance concrete to be utilised. This would combine some of the main advantages of the current sprayed method with the premixed method, namely, a high fibre content, controlled fibre orientation and the increased limit of proportionality of the concrete.

B Improving the new mould system.
The new mould system developed and tested in this research is still at its conceptual phase, and should be developed further to resolve the problems of compatibility between the different polyurethanes used for the mould. In addition, alternative materials to polyurethane-based foams should be tested, since they are currently non-recyclable. An edge system should be developed that can accommodate the edge-return not being projected from the surface and also capable of accommodating a full range of different angles from the surface.

C Development of a fully digital and automated production method.
The novel manufacturing method should be developed further to include plug-in tools with all the embedded limitations highlighted in this research. The plug-ins would allow architectural forms to be generated where the feasibility of manufacture and the associated cost is known. To realise a fully digital and automated production process a production line needs to be developed that integrates the plug-inns, the manufacture of the new mould system, and the new developments of the sprayed system into a single line. This could be achieved by adapting current automated premixed production lines.

D Expanding the scope of a flexible table.
A new flexible table specifically designed for the new mould system should be developed that can accommodate geometries with smaller radii than 0.5m, panel heights larger than 0.4m, and panel sizes of at least 3m x 3m. Potentially the flexible table could be integrated into a fully automated production line for “printed” GFRC. The speed of this new line would depend on the curing time of the foam material used for the new mould. And ultimately the curing time of the GFRC.

§ 7.8.2 Current barriers limiting future research

Glass fibre meshes has been developed for thin-walled GFRC, however they cannot be integrated into double curved and free-form shapes without creating folds in the panels.

The tensile capacity of the GFRC is one of the limiting factors. If the tensile capacity of the GFRC was increased it would allow for longer spanning elements and thereby reducing the cost of sub-structure, as long as the deflection of the panel does not become critical.

Maximum sizes of panels without integrated sub-structure is limited in size by the maximum bending capacity of the GFRC material, making it difficult to manufacture panels larger than 3m in single sided span without the panels thickness increases significantly and the panels are very difficult to handle.

The second challenge with panels larger than 3m is transportation, because of road constraints panel sizes higher then 3m is difficult to transport without special transportation arrangements; the additional cost is normally not viable for buildings with many oversized panels.

§ 7.9 Recommendations for the market

Coordination between the different trades in the building process will enable more complex geometry thin-walled GFRC building envelopes to be realised. The feedback loops between the manufacturers, the architects and designers need to be streamlined and the limitations and barriers of each production method need to be considered as part of the design of the building envelope. To maximise the feasibility of thin-walled GFRC it is recommended that the appropriate production method is identified early in the design process. The manufacturers need to invest in facilities so they can handle complex geometry thin-walled panels and the logistics of the often, many unique, panels. During the execution of manufacturing a plan for the logistics need to be established whether the panels are produced according to the installation sequence or the optimum manufacturing sequence, with many similar panels being cast in sequence. The last requires storage space and an identification system to manage the building site at a later point in time. The production of thin-walled GFRC elements based on optimum manufacturing sequences is the most cost effective solution but requires additional storage space. For innovative complex geometry panel shapes it is recommended that the client invests time and finances on detailed tests of complex geometry thin-walled GFRC. If this is done risks and cost will be reduced.

§ 7.10 Contribution to knowledge

This research work has identified key knowledge gaps in the manufacturing process of complex geometry thin-walled GFRC. A novel manufacturing method has been proposed and, together with a patented mould system, has contributed to the knowledge base of thin-walled GFRC production. The results are evident in the test samples manufactured and the 10m tall self-supporting hyperbolic shell that was fabricated using the new mould system and installed in February 2016.

During the research when the flexible table was tested if became apparent that in intermediate step had to be developed to advance thin-walled GFRC further. Because of the knowledge gap for complex geometry thin-walled GFRC this research is original and unique.

The proposal for a novel manufacturing process will advance complex geometry further and more building envelopes will be realised based on this research.

The contribution to science and construction is that with this research is will be more cost effective to build complex geometry building envelopes with thin-walled GFRC instead of using GFRP which is non-recyclable, and the novel manufacturing process will ensure less material usages compare to existing manufacturing processes.

The contribution to society is that the new mould system and the proposed digital and fully automated manufacturing process will enable more buildings with complex geometry envelopes to build with GFRC instead of GFRP which is a flammable material. The GFRP poses a significant risk of fire so the use of GFRC would mitigate this risk because GFRC is non-flammable.

8 List of Publications

Journal Papers

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.

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.

The impact of a new mould system as part of a novel manufacturing process for complex geometry thin-walled GFRC . **Henriksen, T., Lo, S. and Knaack, U.** s.l. : Taylor & Francis, March 2016, Architectural Engineering and Design Management.

A new method to advance complex geometry thin-walled glass fibre concrete elements. **Henriksen, T., Lo, S. and Knaack, U.** s.l. : Elsevier, April 2016, Journal of Building Engineering.

Developing and testing a novel manufacturing method for complex geometry thin-walled GFRC panels by fabricating a 10m high, self-supporting GFRC hyperbolic shell. **Henriksen, T., Lo, S. and Knaack, U.** s.l. : Elsevier, Journal of Building Engineering (Under review).

Conference Papers

Innovative Complex geometry GFRC, Thin-walled concrete panels for future building envelopes, **Henriksen, T., Lo, S. and Knaack** , Facades Tectonics, Los Angeles, USA, 2016

Advancing the architectural application of complex geometry GFRC, **Henriksen, T., Lo, S. and Knaack** , GRCA, Dubai 2015

FRC in Complex geometry Facades, **Henriksen, T. and Knaack, U**, Befib, Minho, Portugal 2012

Structural challenges of textile reinforced FRC panels, **Henriksen, T. and Knaack, U**, 9th Fib Symposium, Karlsruhe 2012

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", WO2014138759A1, **Henriksen, T., and Raun, C.** (2013, March 13).

Curriculum vitae

Thomas Henriksen

Nationality	Danish
Year of Birth	*1976*
Profession	*Technical Director*
Specialisation	*Façade Engineering*
Position in Group	*Global Leader Façade Engineering*
Year of joining Group	*2016*

Key qualifications

Currently Technical Director and Global Leader Façade Engineering at Mott MacDonald, joining in 2016. Previous roles include Technical Director at Waagner Biro (2011-2015) and Seele (2010-2011), Project Manager Façade Package at IAV Construction (2007-2010), Senior Structural Façade Engineer at Arup (2004-2007).

A high level of experience in design across a wide range of buildings and infrastructure projects including; architectural competitions, direct liaison with clients, interpreting the clients' requirements and developing and presenting design proposals; Contract negotiations; design development and detailing; coordinating interfaces between sub-contractor packages and overseeing construction on-site; reviewing progress against contractors programs and maintaining on-site quality.

Education and professional status

- MSc Engineering, Technical University of Denmark, 2002
- Member of the Institute of Structural Engineers (MIStructE), 2008
- Chartered Engineer (CEng), 2008

Experience record

2016 – present

MOTT MACDONALD GROUP
Technical Director and Global Leader Façade Engineering

2011 – 2016

WAAGNER BIRO
Technical Director

Etihad Museum - New Museum building for the union of the Arab Emirates, Complex geometry Steel roof clad with Double curved GFRC. Complex Glass fin façade with 12m in-plane inclined glass fins.
Louvre Abu Dhabi Dome - Dome of Louvre Abu Dhabi helped of the tender, and key façade details and main reviews.
Lakhtar Centre Multifunction Building St. Petersburg - Multifunction building with inclined 16m Glass fin facades. Involved in initial design stages and design reviews.
Grand Museum of Egypt 2014 - Tender of the Simpinsky Stone wall and the facades for the museum.
Guggenheim Abu Dhabi, Designed by Frank Gehry - Tender process 2010 - 2015, workshop with Gehry in LA, detailed tender process.
COOP HQ, Manchester - New QH for COOP in Manchester, Complex geometry roof and façade, Tender process and design reviews.
Manta Project, Lavestock UK - Tender development of the Manta project with Arup and Heatherwick Studio. Winning presentation with Thomas Heatherwick 2010 for Architectural design competition.
Tottenham Court Road, London - New Glass entry for LU. Tender process and development of structural glass proposal. 2nd Price.
Welcome Trust, Cambridge - Steel and glass roof with cold bent IGUs. Design development of Key details and Design reviews.
Blavatnic, Oxford - Unitzed curtain wall, for building design by Herzog de Meuron, Design Reviews.
Crossrail Paddington, Crossrail Limited, Weston Willamson Architects - New glass roof over the new Crossrail and Network Rail station entrances (the glass roof has an extreme bomb blast requirement): Design Director and Client Liaison.
Maersk, Panum - New Medical university tower, high performance adaptable façade, designed by CF Møller Architects: Tender Manager, Design Director and Client liaison.
Glazed Link, Manchester, Simpson Haugh Architects - Structural glass building with a geometrically complex mirror-polished stainless steel roof, designed by Ian Simpson: Tender Manager, Design Director and Client Liaison.
Sowwah, Abu Dhabi - New glass roof in the financial district in Abu Dhabi, designed by RFR. Complex geometry and significant earthquake requirements: Design Director, Client Liaison.

2010 – 2011

SEELE
Technical Director

London Olympic Main Stadium - Design and installation of membrane roof.
London Olympic Swimming Pool - Olympic Swimming pool designed by Zaha Hadid, Detailed design of Glass façade, Olympic mode and Legacy mode.

2007 – 2010

IPC CONSTRUCTION
Project Manager Façade Package

New National Library, Reykjavik - Design development of the New National Library.
ARoS Your Rainbow Panorama, Aarhus - The Rainbow walkway is an art piece by Olafur Eliasson, using glass as primary structural element, Architect SHL: Design Director for the structural glass, Liaison with client and Municipality for planning.
Harpa, Concert Hall, Reykjavik, HLA Architects - Concert Hall is part of a new development of the old harbour. The facades are designed by the artist Olafur Eliasson, and feature one of his art pieces, Project Manager. Project awarded the Mies VDR Prize in 2013.

2004 – 2007

ARUP FAÇADE ENGINEERING
Senior Structural Façade Engineer

Danish Radio Seg. 2 and News studio - Seg-2 is the News House for Danish Radio, designed by Dissing & Weitling. Detailed design and analysis of bespoke cladding systems, structural glass elements and a bespoke steel structure for the glass ceiling.
St. Martin in the Fields - New Entrance to the Crypt. designed by Eric Perry Architects. Design intent of the structural use of glass for the main entrance.
Mount Stuart Visitor Centre - Refurbishment of the Mount Stuart Visiting Centre. Structural Glass stabilizing the building.
More London Plot 3 - New office building by the River Thames, designed by Foster and Partners. Design intent of the double glazed façade for the main entrance.
Der Spiegel new HQ, Hamburg - Architect competition 1st price, designed by Henning Larsen.
Riverside 1, Dublin - Double skin façade on new office building in Dublin. Design development of double skin façade.

Microsoft India - New office building. Structural design of the glass structure carrying and supporting the outer glass panes.

Fitzroy close, London - Entry building for private house. Complex geometry steel and glass façade. Structural development.

The Rainbow project, Dublin - New development in Dublin. Including a 130 m tall residential building. Designed by Henning Larsens Architects.

Naturvidenskabens Hus, Bjerringbro, Denmark - New Science educational building designed by Nord Architects. Architectural competition 1st Price.

Vibenhus development, Copenhagen - New office building designed by BIG architects. Architectural competition 1st price.

Aarhus New Hospital, Denmark - Design competition for new build hospital 200.000m2. Contract sum 700 mill GBP. 2nd price in architectural competition. Office Manager Arup Denmark.

New national Aquarium Copenhagen - Design competition with HLA. 3rd Price.

Grand Museum of Egypt 2006 - Grand Museum of Egypt designed by Heneghan and Peng. Design development of the Light court.

Malmo City Tunnel - Design intent for two canopy entrances for a new underground train station in Malmo. Both entrances consist of double curved steel structures. Senior Structural engineer.

Potters Fields - Potters Field, is a residential development in London, designed by Ian Richie. The project involved the use of structural use of glass fiber reinforced plastic. The GFRP supported an external walkway, through the vapor barrier.

2002 – 2004

B&K/ ARUP DK

Junior Structural Engineer

Fritz Hansen - Design of structures for an administrative building for an International furniture company. Client: Republic of Fritz Hansen.

Høje Brygge - Design of structures for 17-storage circular prefabricated building. Høje Brygge, Ålborg. Client: Kristensens Ejendomme A/S.

Private wooden summerhouse, Denmark - Structural development of summer house. Details design and production drawings.

DFDS Ferry terminal - Design of structures for a new ferry terminal for DFDS in the port of Copenhagen, floor-space: 4500 m2. Client: Københavns.

Zero Carbon houses, Ringgården, Denmark - Design development with SHL architects 1st price in Design competition for 40 Zero Carbon houses 2003. Structural concept design.

LANGUAGE CAPABILITY

Danish	:	Mother tongue
English	:	Spoken – fluent; written – fluent; reading – fluent
German	:	Spoken – fluent; written – fair; reading – good
Norwegian	:	Spoken – Fair; written – fair; reading – good
Swedish	:	Spoken – Fair; written – fair; reading – good
Icelandic	:	Spoken – Fair; written – fair; reading – good
Chinese	:	Spoken – basic; written – none; reading – none

PUBLICATIONS

Glass and Façade Engineering Conferences

"Glazed Link, Complex geometry stainless steel artwork supported by structural glass walls", Advanced Building Skins, Graz 2015
"Unobtainium, Solving the impossible", Façade 9, Delft 2015
"Structural glass fin under blast loading", GPD, Tampere 2015
"Digital Design, design to manufacture", Henderson Colloquium, Cambridge, Christ Collage 2014
"Future of the Glass Industry", GPD, Tampere 2013
Chairman Session, GPD, Brazil 2012
"Bomb-blast requirement in Public Buildings", IStructE, London 2012
"Future application of structural use of glass", Challenging Glass 3, Delft 2012
"Free form architecture for low carbon buildings", Façade, Bath 2012
"Bomb-blast requirement in Public Buildings", GPD, Tampere 2011
"Free form Architecture from concept to installation", IGS, glass publication 2011
"Design of Glass for High Short Duration Wind Loads", Challenging Glass 2, Delft 2010
"Bomb-blast requirements on facades", GlasTec, Dusseldorf 2010
"The challenge of future façade renovations", Façade 2010, Luzern 2010
"Anisotropy and Optical distortion in architectural glass, can it be controlled" "ARoS, Your Rainbow Panorama by Olafur Eliasson", GPD, Tampere 2009
"Design of large point fixed glass with a bespoke fixing", Challenging Glass, Delft 2008
"Reykjavik New Concert Hall", GPD, Beijing 2008

Doctoral Work

Conferences

"Advancing the architectural application of complex geometry GFRC", paper, GRCA, Dubai 2015
"FRC in Complex geometry Facades", paper, Befib, Minho, Portugal 2012
"Structural challenges of textile reinforced FRC panels", paper, 9th Fib Symposium, Karlsruhe 2012
"Future of GFRC", presentation, Innsbruck 2011

Journal Papers

"A new method to advance complex geometry thin-walled GFRC elements", Elsevier, Journal of Building Engineering, 2016, Issued.
"The impact of a new mould system as part of a novel manufacturing process for complex geometry thin-walled GFRC", Taylor & Francis, Architectural Engineering and Design Management, 2016, Issued.
"Advances in the application of thin-walled GFRC", ASTM International, Advances in Civil Engineering Materials 2015, Issued.
"An innovative approach to manufacture thin-walled GFRC for tomorrow's architectural buildings envelopes with complex geometry", Elsevier, Journal of Building Engineering, 2015, Issued.

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", 2013