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.

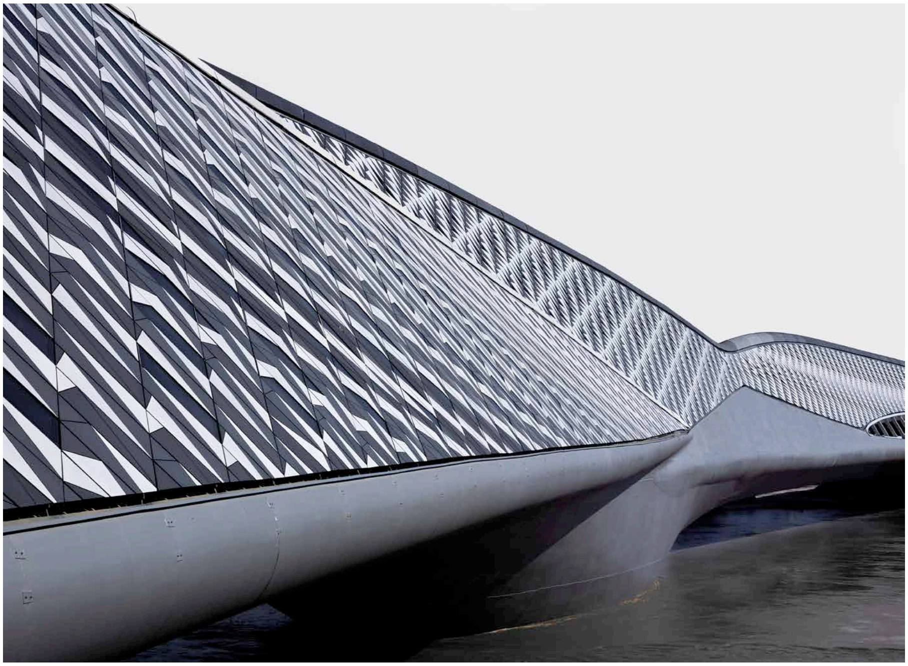

FIGURE 1.1 Expo Bridge in Zaragoza, ZHA Architects (Photo Rieder GmbH)

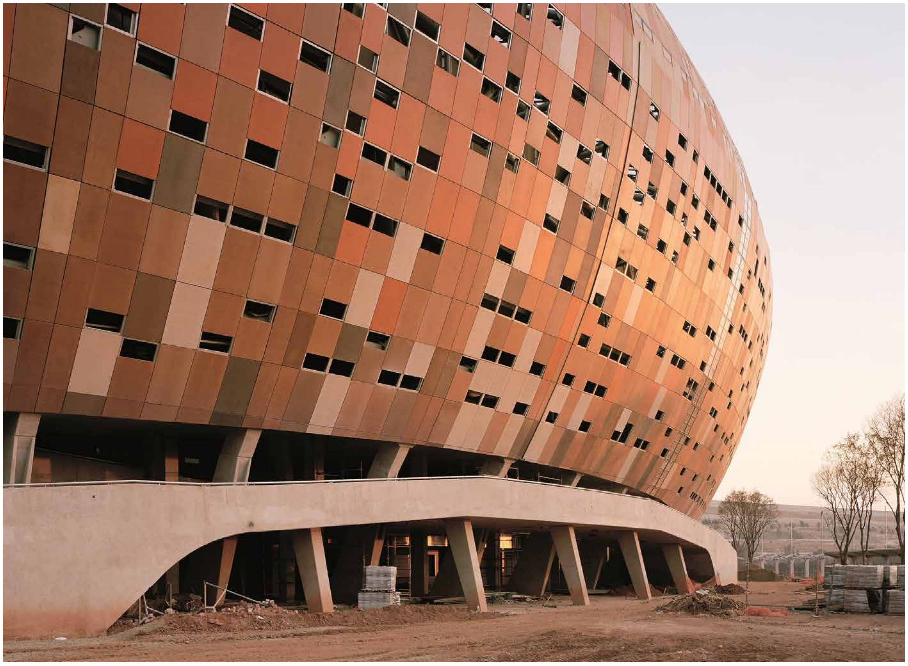

FIGURE 1.2 Soccer City stadium, HOK Architects (Photo Rieder GmbH)

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.

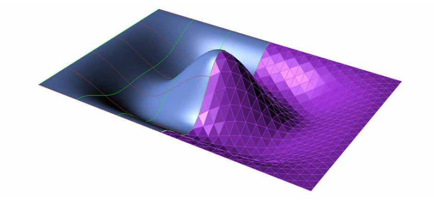

FIGURE 1.4 Tessellated free-form

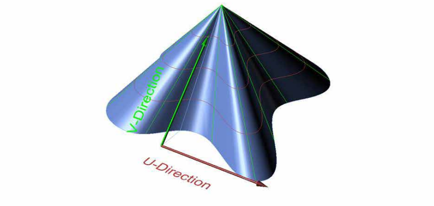

FIGURE 1.5 Single curvature

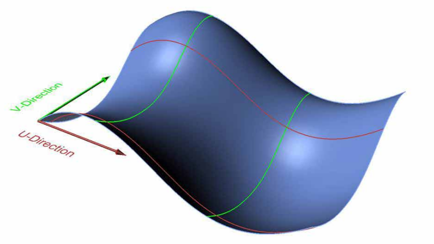

FIGURE 1.6 Double curvature

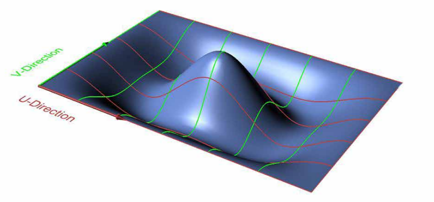

FIGURE 1.7 Free-form

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.

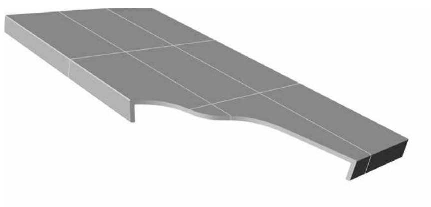

FIGURE 1.8 Flat panel with an edge-return

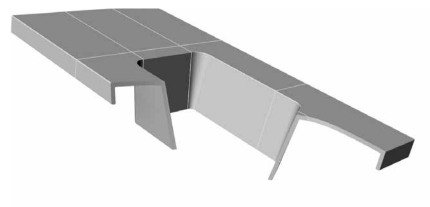

FIGURE 1.9 Flat panel with an edge-return and a panel offset

§ 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.

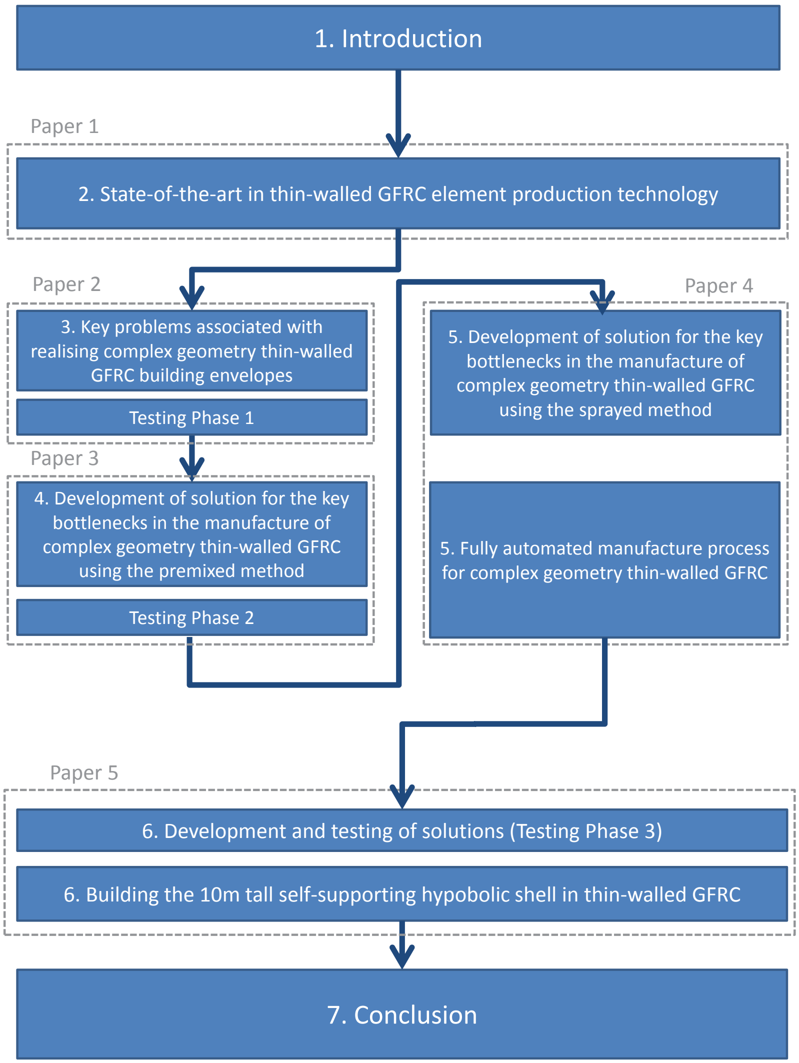

FIGURE 1.10 The dissertation outline and the order of the chapters.

§ 1.11 References

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

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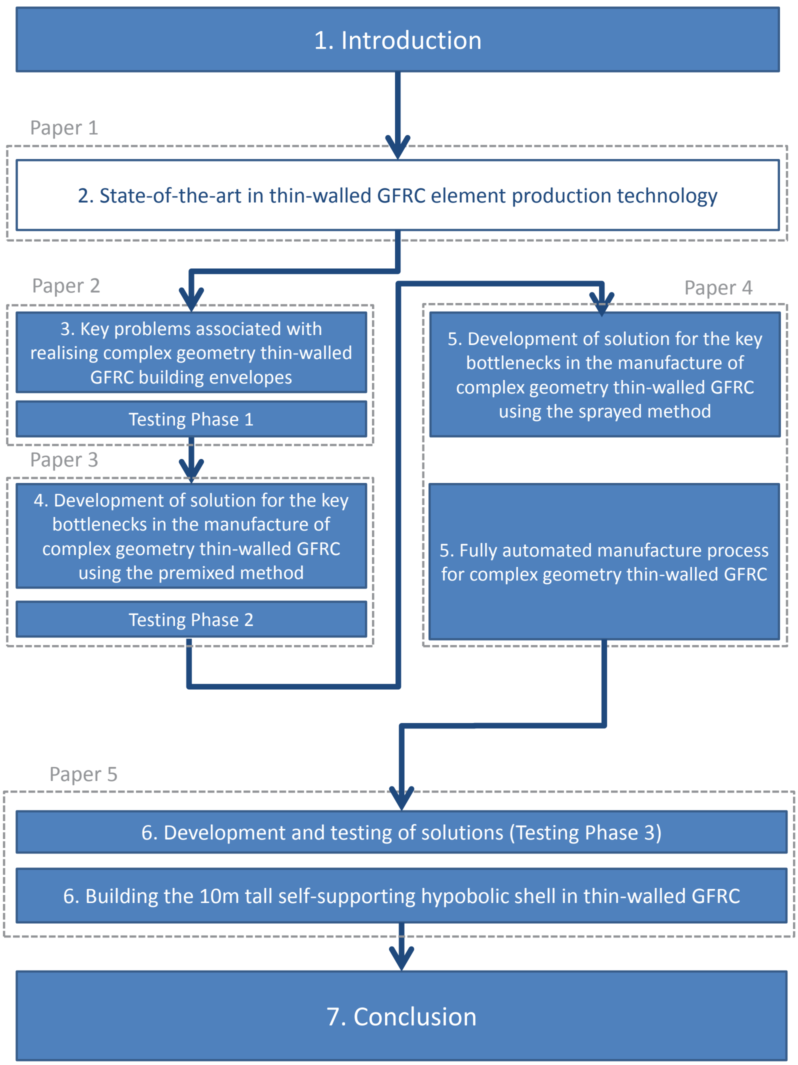
1. Introduction
Paper 1
2. State-of-the-art in thin-walled GFRC element production technology
Paper 2
3. Key problems associated with realising complex geometry thin-walled GFRC building envelopes
Testing Phase 1
Paper 3
4. Development of solution for the key bottlenecks in the manufacture of complex 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