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.

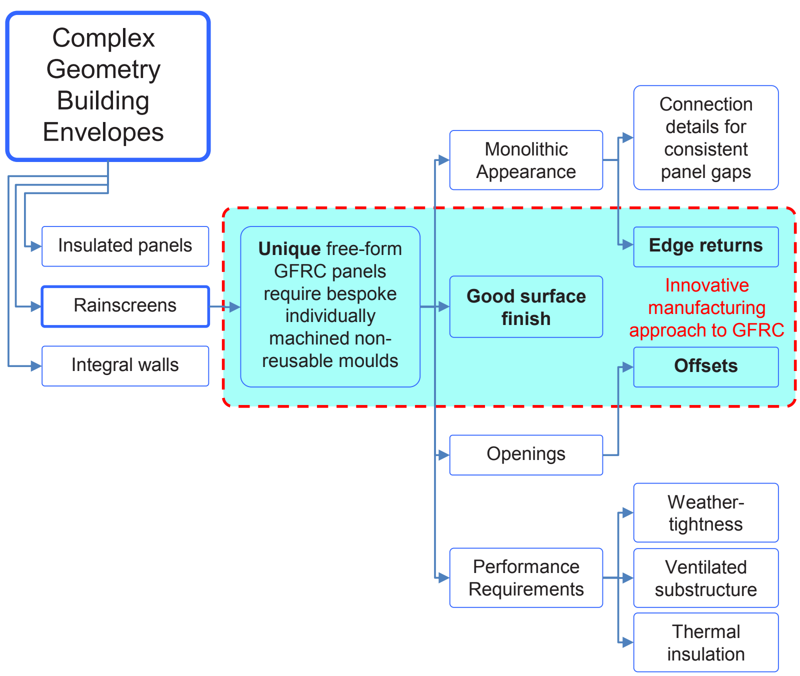


FIGURE 7.1 An innovative approach to the challenges of complex geomerty GFRC rainscreen cladding

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-return	√ (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.

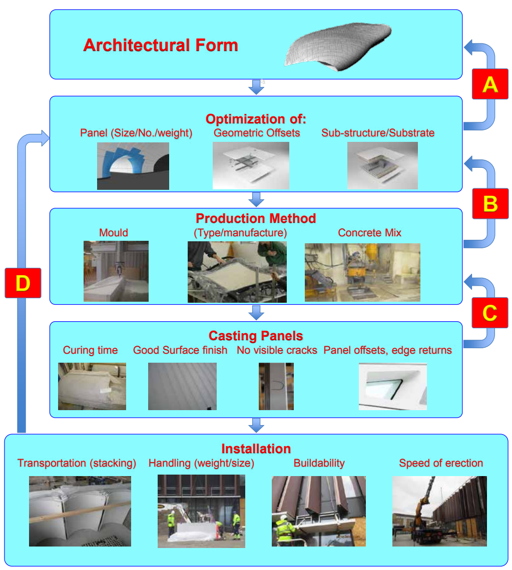
** Curing time reduces the usage of the flexible tables.

*** 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.

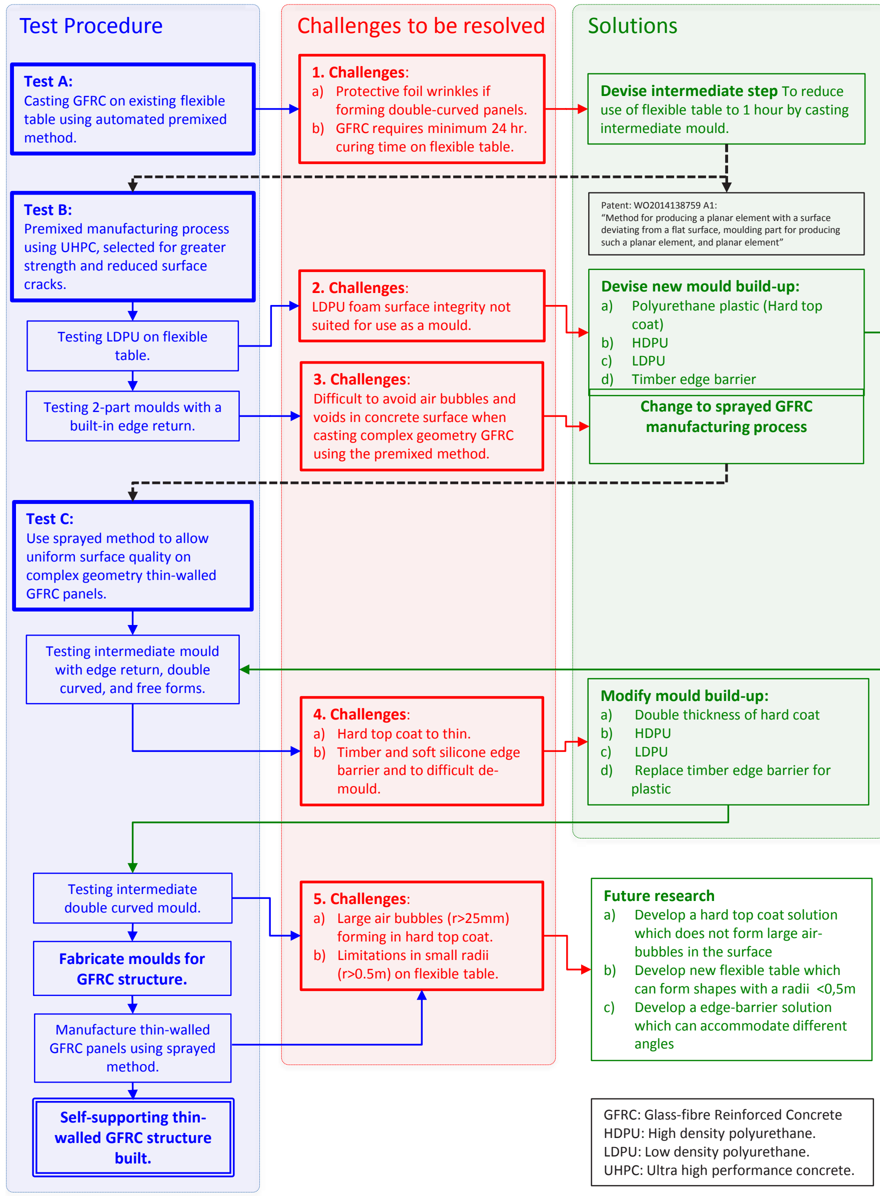


FIGURE 7.3 Development of experimental procedure for thin-walled GFRC panels

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.

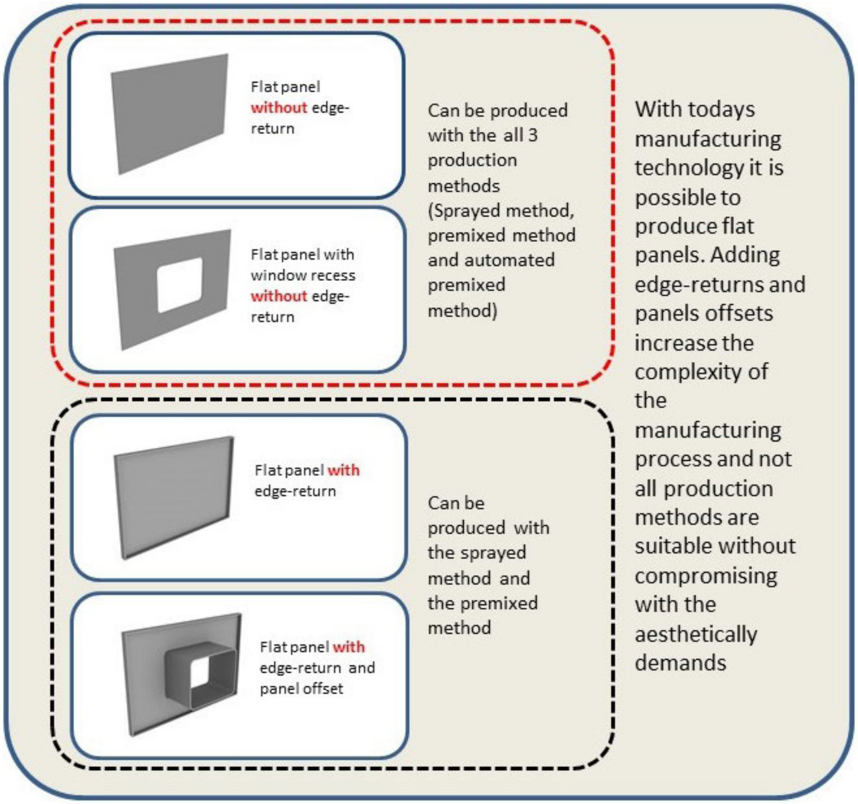


FIGURE 7.6 Recommendations for flat thin-walled GFRC panels with an edge-return and panel offset

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.

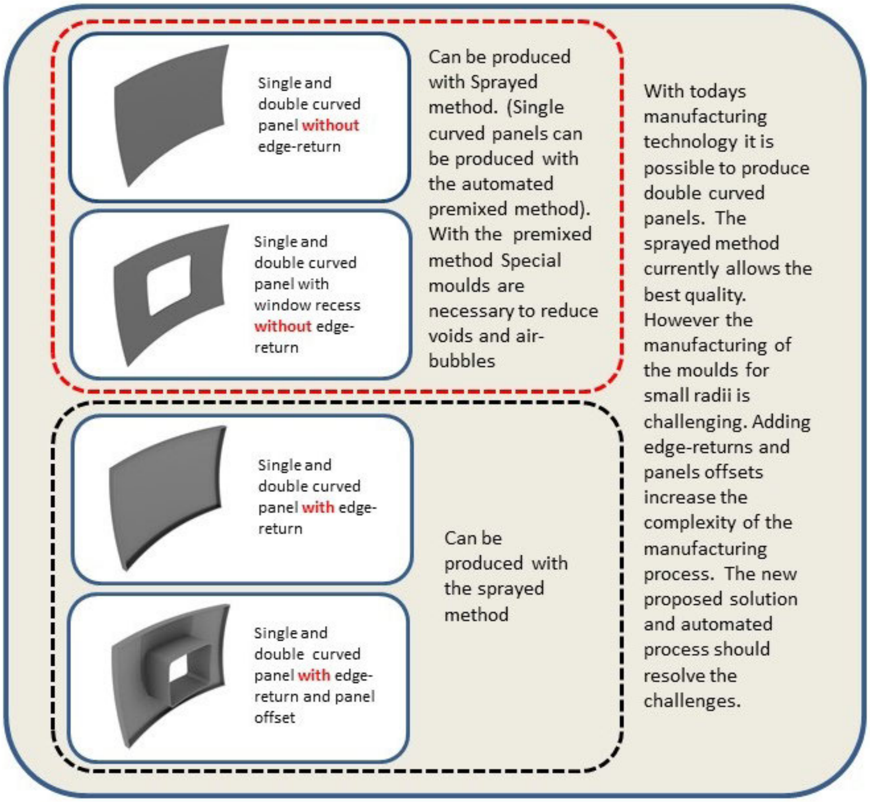


FIGURE 7.7 Recommendations for single and double curved thin-walled GFRC panels with an edge-return and panel offset

§ 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.

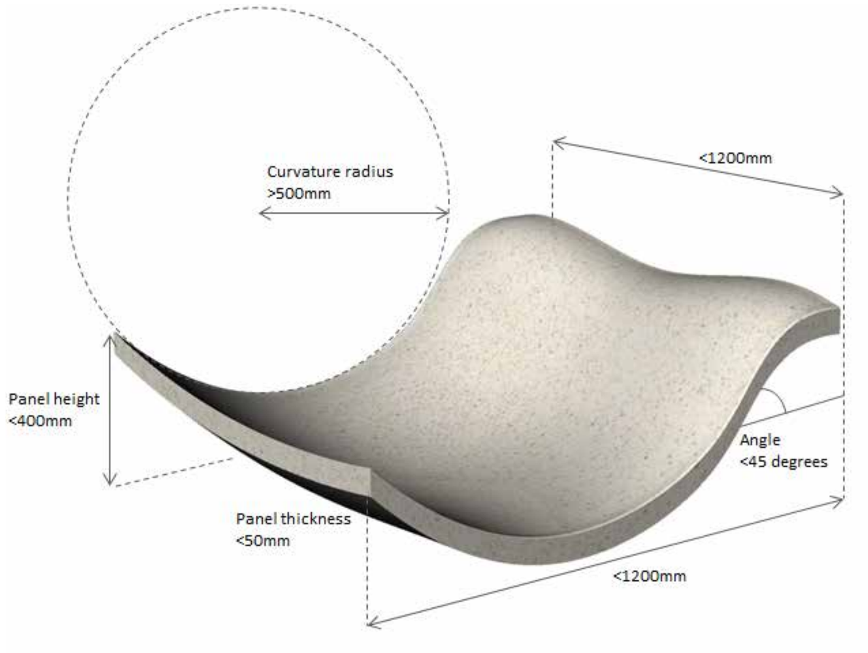


FIGURE 7.8 Limitations in flexible table used in this research

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.