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.

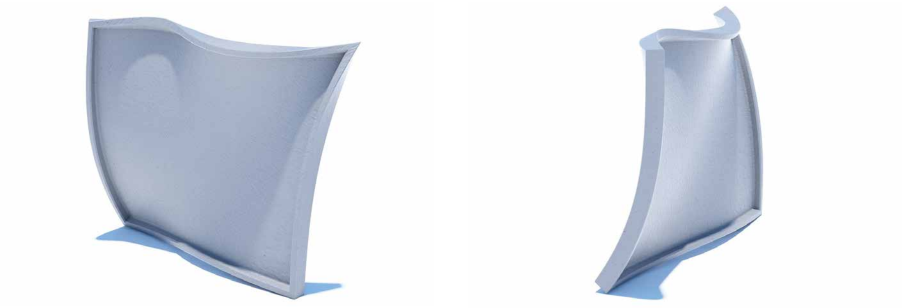

FIGURE 2.1 Renderings of complex geometry thin-walled GFRC.

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.

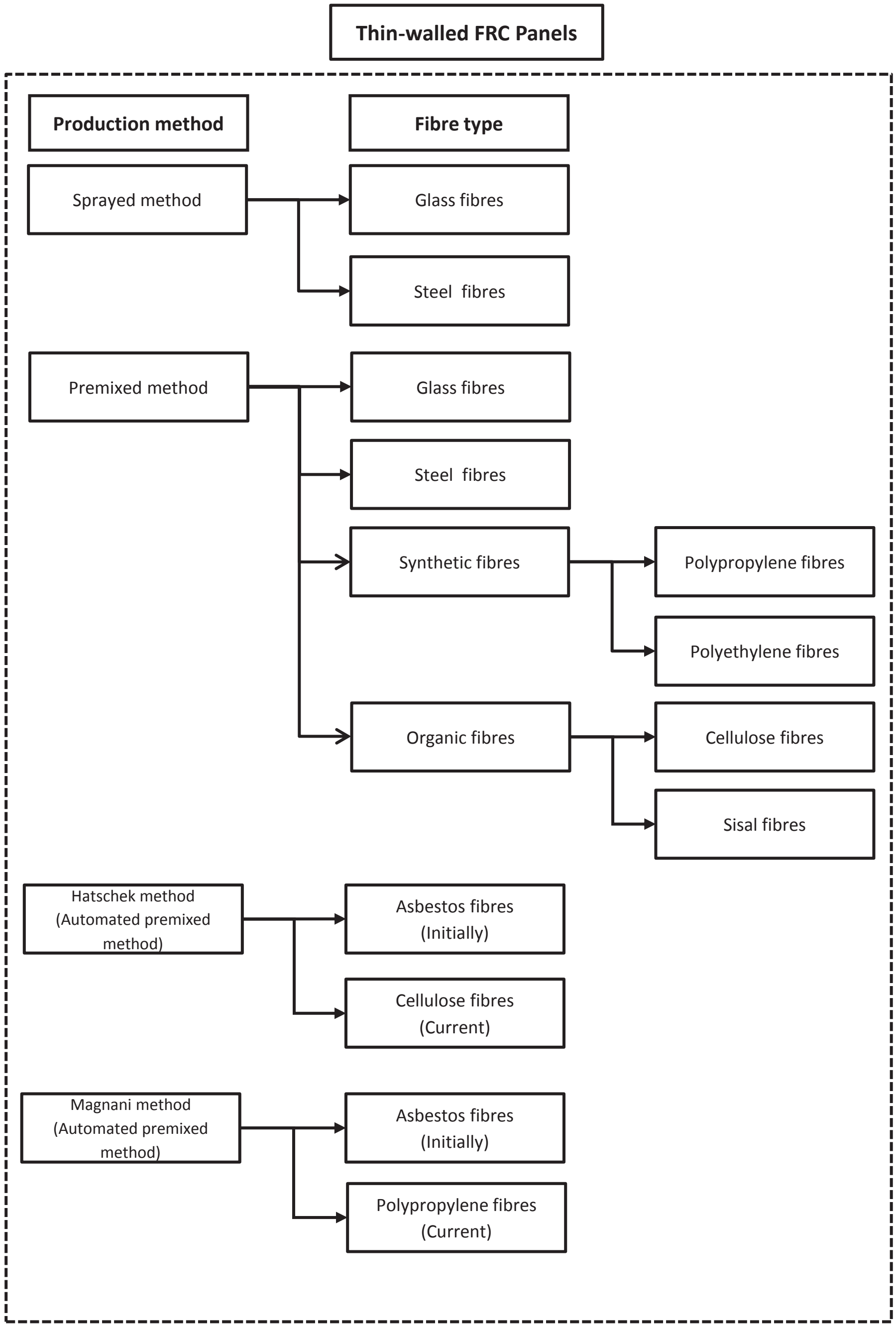

FIGURE 2.2 Production methods for reinforced fibres concrete.

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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/m^3	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.

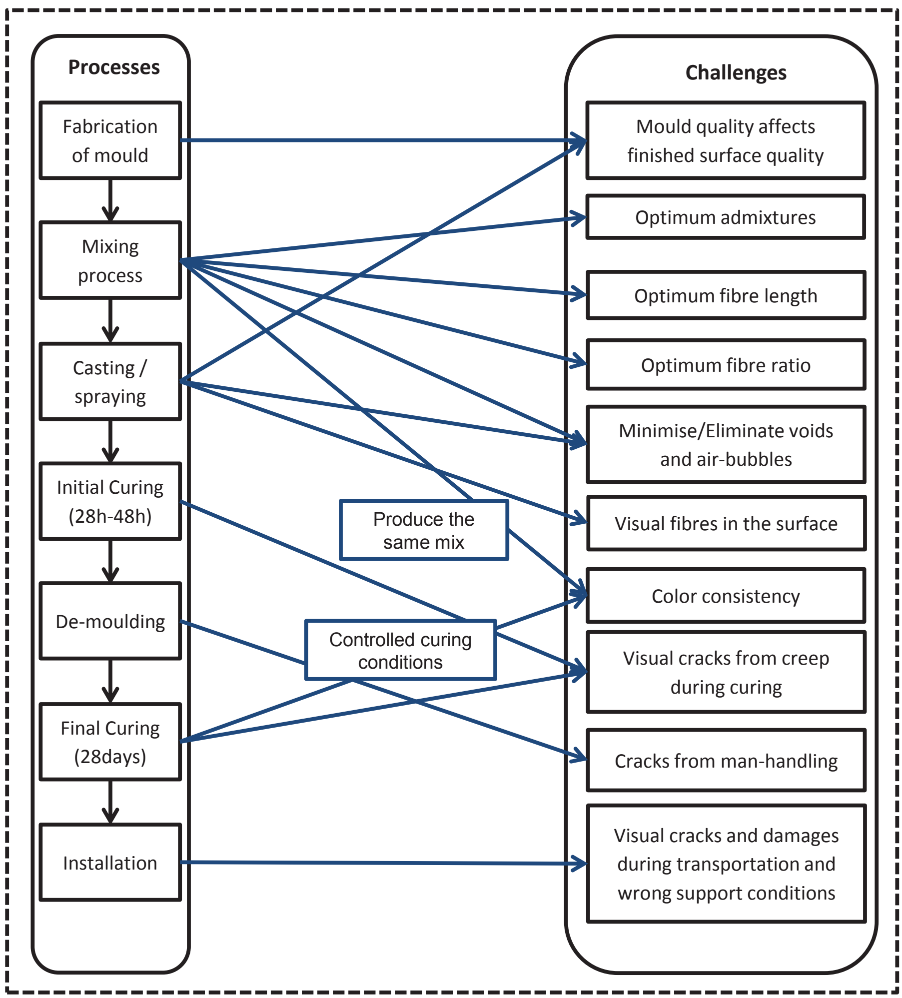

FIGURE 2.6 Diagram showing the link between the processes and challenges for thin walled GFRC elements.

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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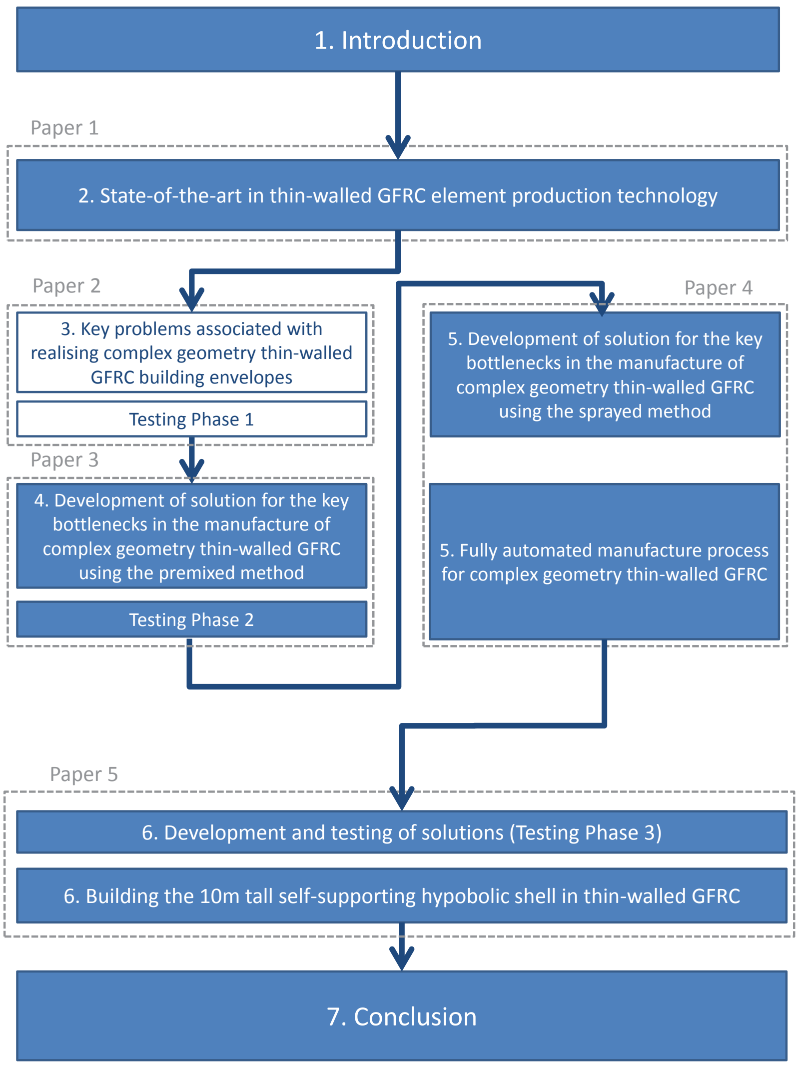
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