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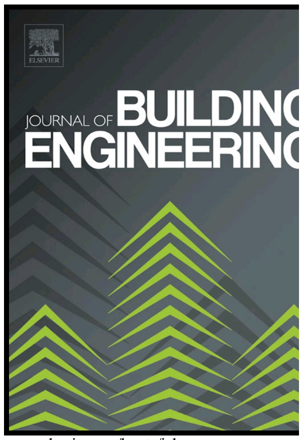

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An innovative approach to manufacture thin-walled glass fibre reinforced concrete for tomorrow's architectural buildings envelopes with complex geometries

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Abstract

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

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

1. Introduction

Glass fibre reinforced concrete (GFRC) elements have become a sought after cladding material since their first introduction as rain screen cladding for buildings. The first buildings in the UK with GFRC cladding were designed in the 1970s. These buildings were designed with geometrically simple GFRC elements based on a flat building pattern. As building envelope geometries become more complex the aesthetic demands of designers become more challenging. This paper presents an innovative approach to the manufacture of GFRC as façade cladding for buildings with a range of complex geometries. The current state of the art in terms of thin-walled GFRC elements with complex geometries, and the production methods that can be used to achieve the intended panel geometries, are defined, but the structural performance of the thin-walled GFRC elements is outside the scope of this paper. The intent is to define guidelines for an innovative approach to advance thin-walled GFRC elements with complex geometries. An illustration of the scope of the work presented in this paper is highlighted in Figure 1.

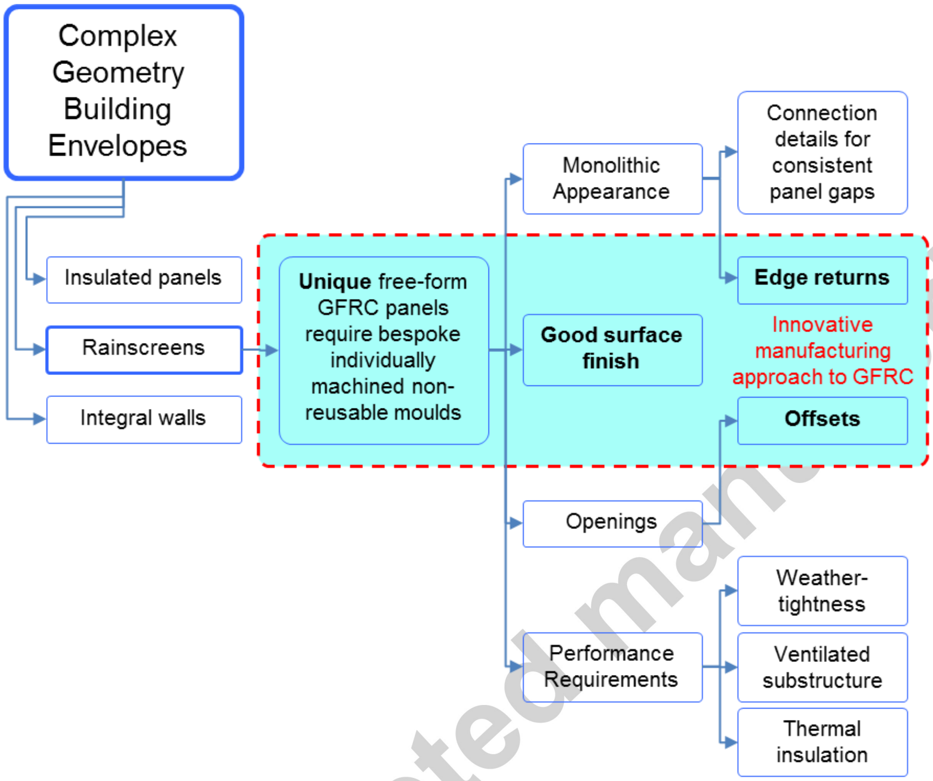


Figure 1 An innovative approach to the challenges of complex geomerty GFRC rainscreen cladding.

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

- Insulated panels
- Rain-screens
- Integral walls

The focus of the presented research is thin-walled GFRC elements as a rain screen. Insulated GFRC panels and GFRC integral walls are outside the scope of this research, since GFRC elements with complex geometries first need to be solved for thin-walled GFRC elements before the technology can be applied to insulated panels and integral walls. The main challenge of 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 (edge-returns are shown in Figure 2 and in Figure 5). This requirement for such bespoke free form GFRC panels with good surface quality, edge-returns and offsets (an offset is shown in Figure 3) cannot be met with the current production methods and existing research also does not describe in detail the aesthetic requirements that may be achieved with different production methods.

Advancing the edge-detailing for complex geometry buildings is necessary to provide a substantial and monolithic appearance of the building, (Bishop E. , 2014). The edge-return is defined as an up-stand from the edge of the panel as shown in Figure 2. If GFRC elements have an edge-return or an offset, (required for openings), from the primary surface in addition to a complex geometry, then the manufacture of the GFRC element is even more complex.

Figure 2 Corner of a GFRC panel with an edge-return, the GFRC panel has been produced with the premixed method

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

The offset of the surface required for openings, is defined as a cut out in a surface that is translated parallel to the primary surface, as used in the King Abdullah Petroleum Studies and Research Centre in Riyadh, Saudi Arabia (Bishop & Wilson, 2011) and on The Broad Museum, in Los Angeles, USA (Feirabend, Emami, & Riedel, 2014). An example of a thin-walled GFRC element with an offset developed for the King Abdullah Petroleum Studies and Research Centre is shown in Figure 3.

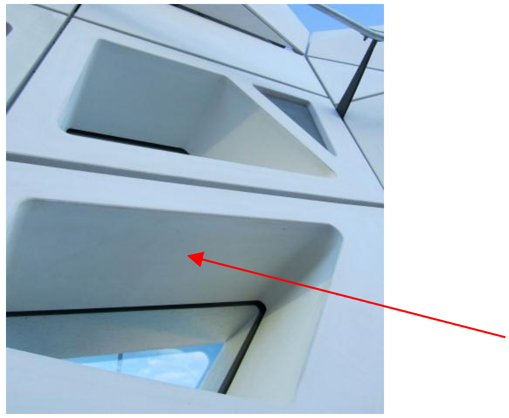


Figure 3 GFRC element with an offset at window return (indicated with red arrow) to allow for a window recess, produced using the premixed method.

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

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

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

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

2. Architectural application of 1, 2, 3-D and freeform thin-walled GFRC

Thin-walled GFRC as an architectural cladding material has been used since its initial development in the 1970s (Fordyce & Wodehouse, 1983). The material was used because it was a durable and relatively lightweight weather-resistant material that could easily be handled. It could also be easily moulded to specific dimensions and shapes, and the cost of producing the elements was low compared to similar durable materials such as glass. (With glass it was not possible to fabricate the edge-returns and offsets

[1] The most common production methods are the sprayed method, the premixed method and the automated pre-mixed method. The different production methods for thin walled GFRC are described in in detail and compared in (Henriksen, Lo, & Knaack, 2015) (Fordyce & Wodehouse, 1983) (FIP State of art report, 1984) (ACI 549.2R, 2004)

required to obtain a monolithic appearance of the building.) Such properties made thin-wall GFRC a sought after material with the first examples produced as modular elements at 30 Cannon St building in London, UK in 1977, and, the UOP Fragrance, Tadworth, Surrey UK in 1978 (Brooks & Meijs, 2008). In the last decade thin-walled GFRC has been used for landmark buildings with complex geometries because of the introduction of advanced geometric software tools capable of creating such free form building envelopes (Pottmann, Asperl, Hofer, & Kilian, 2007).

Thin-walled GFRC elements are predominantly used as rainscreen cladding because a thin (10-20mm) non load-bearing element can be handled easily. Thin-walled GFRC elements are single units that are fixed to a substructure, such as the Expo Bridge in Zaragoza, Spain (1996), and the Soccer City stadium in South Africa (2010). However, for the Heydar Aliyev Center, Baku, Azerbaijan (Bekiroglu, 2010) thin-walled GFRC was initially proposed for its complex free form geometry but due to the complexity of the geometry all panels 1m above the concourse were produced using GFRP (Glass fibre reinforced plastic) panels, i.e. the majority of the single curved panels, double curved panels and free form panels on the building. The panels on the concourse including 1m of the building were produced with GFRC, but consist of mainly flat geometries (Dale, 2015).The cladding material was changed due to the high cost of producing many bespoke complex geometry thin-walled GFRC panels. Figure 4 shows the production of the GFRP panels for the Heydar Aliyev Center.

Figure 4 Production of GFRP cladding panels for the Heydar Aliyev Center

Other recently built examples of rain-screen GFRC cladding is the newly opened museum Foundation Louis Vuitton in Paris, France (2014) (Aubry, Bompas, Vaudeville, & Corvez, 2013). A further two landmark buildings in the Middle East are under construction, the King Abdullah Petroleum Studies and Research Centre in Riyadh, Saudi Arabia (Bishop & Wilson, 2011) and the Qatar National Museum in Doha, Qatar, both with GFRC clad areas of approximately 100.000m^2. All these examples exhibit different geometric complexity, some with solely thin-walled flat GFRC panels **without** an edge-return, and others with thin-walled freeform GFRC panels, **with** an edge-return.

In order to distinguish between different complex geometry thin-walled GFRC elements it is necessary to classify their shape in terms of their complexity and also the range and scope of their associated manufacturing process possibilities. A detailed description of the geometric categories of thin-walled GFRC elements is described by (Henriksen & Schiftner, 2012), (Eigensatz, Dreuss, Schiftner, Kilian, Mitra,

& Pottman, 2010), (Floery & Pottmann, 2010) and (Pottmann, Asperl, Hofer, & Kilian, 2007). The range of geometries were divided into 4 categories;

1. Flat surfaces
2. Single curved surfaces
3. Double curved surfaces
4. Freeform surfaces

Single curved and double curved geometries have additional sub-groups depending on the severity of curvature and their rate of change in curvature. Table 1 shows the geometric forms with associated examples of GFRC clad buildings or sculptures using thin-walled GFRC elements.

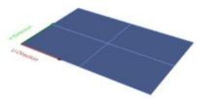
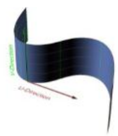
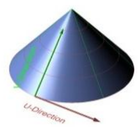
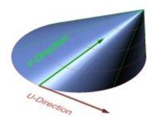
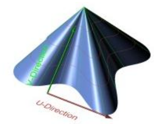
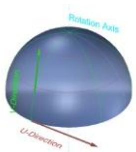
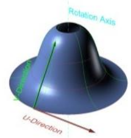
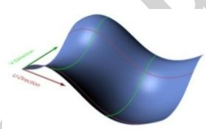
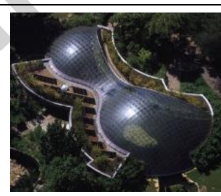
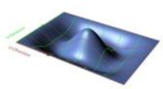
Flat surface				
				
Single curved surface	 Single Curved Surface	 simple cone surface	 Tilted cone surface	 cone-like surface
				
Double curved surface	 Spherical Surface	 Rotational Surface	 Translational Surface	
				
Freeform surface	 Truly Freeform Surfaces			
				

Table 1 Geometric forms with associated examples of GFRC clad buildings or sculptures with thin walled GFRC elements

As the demand for a wider range of complex geometry buildings increases the production technology and the digital machining tools required to produce the GFRC elements is not advancing at the same pace, thus hindering further advancements. Any new approach to advance the design and production of GFRC panels with complex geometries requires a new moulding technique able to produce thin-walled GFRC panels capable of forming all 4 different surface categories. The manufacturing complexity, (the cost, the severity of curvature and their rate of change in curvature), ***increases*** as the design progresses from flat towards more free form surfaces. Conversely the degree of potential repetition ***decreases*** as the design moves from flat to more bespoke freeform panels. This complexity matrix is shown in Table 2 The increase in complexity for thin-walled GFRC panels ranging from flat panels to free form panels combined with the changes in geometric shapes and requirements for an edge-return and offsets in the surface († no panel exist with this geometry).

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

Complexity table	Homogenous surface	Edge - return	Offsets in surface	Constant curvature	Changing curvature	Changing curvature, Edge-return, Offset
Flat	*	**	**	†	†	†
Single curved	**	***	***	****		
Double curved	***	****	****			
Freeform	****			†		

Table 2 The increase in complexity for thin-walled GFRC panels ranging from flat panels to free form panels combined with the changes in geometric shapes and requirements for an edge-return and offsets in the surface († no panel exist with this geometry).

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

3. Challenges in Edge detailing and sealing of thin-walled GFRC

GFRC as building façade cladding is used in contemporary architecture, and its ability to be formed easily and adapted to complex shapes makes it a sought after material. However, the technology to manufacture the complex shaped elements has not followed the development in geometric software tools. The challenge lies in the edge-return detailing of the GFRC elements to act as an architectural device, designed to hide the sub-structure when the joints between the GFRC panels are viewed from obscure angles, and make the façade appear substantial and monolithic (Bishop E. , 2014). Figure 5 illustrates an edge return in the red square compared to GFRC panels without an edge-return, shown in the red oval marker, where the metal sub-structure is clearly visible. However, an edge-return can be difficult to produce for all envisioned geometries, both in terms of cost and minimal defects in the surface (Henriksen, Lo, & Knaack, 2015).

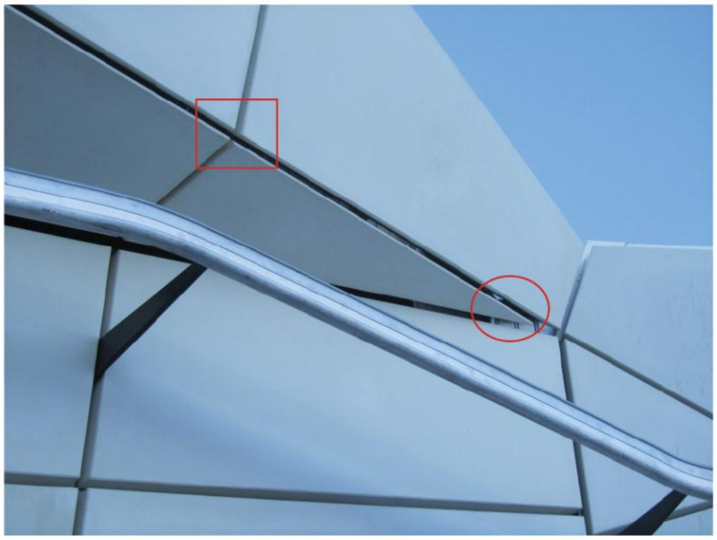


Figure 5 The difference between GFRC elements with an edge-return and without an edge-return. In the red squre the edge-return hides the substructre from obscure angles making the building's cladding appear substaitial and monolitic, where the GFRC elements in the red circle does not have an edge-return and the substructure is visible.

The feasibility of an edge-return depends on the production method. For a flat GFRC panel produced using an automated pre-mixed method such as the Hatschek process (Hatschek, 1901), or similar production methods (Keer, 1990), an edge-return can only be achieved by folding the panel in its "green state" (Henriksen, Lo, & Knaack, 2015). Figure 6 shows a flat GFRC element produced using an automated premixed method without an edge-return and a GFRC element produced using an automated premixed method ***with*** an edge-return. The edge-return has been created by folding the edge of the flat GFRC in the "greenstate" of the concrete (Henriksen, Lo, & Knaack, 2015).

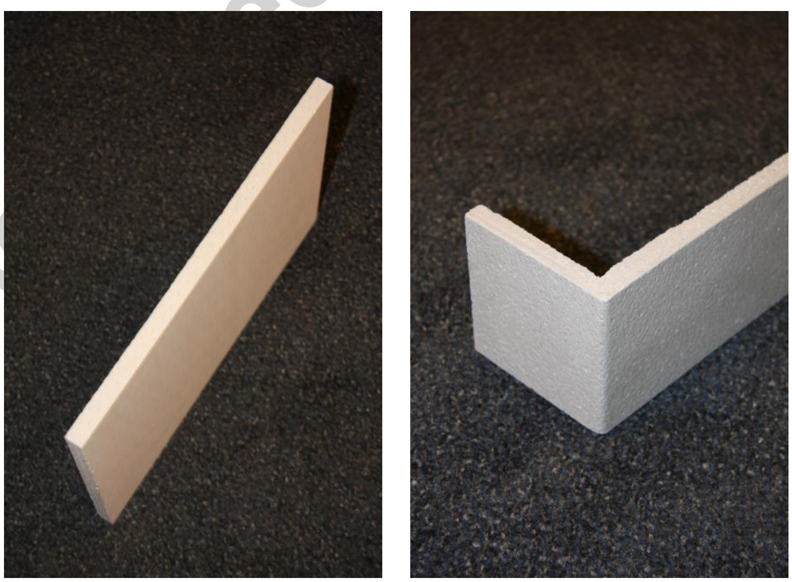


Figure 6 GFRC produced using an automated preixed method elements without and edge-return, and a GFRC element with an edge-return both elements folded in its "greenstate".

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

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

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

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

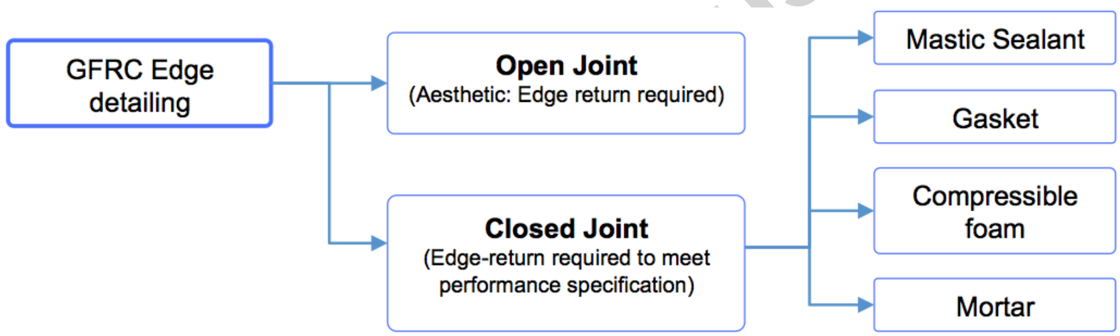


Figure 7 The sub groups of open and closed joints for GFRC edge detailling.

GFRC edge detailing with a closed joint is designed to prevent rain and infestations entering the cavity to provide a primary water-tightness barrier. This allows the secondary water-tightness layer to be re-solved using a membrane system. To close the joint between the GFRC panels, several solutions as shown in Figure 5 may be used, namely;

- Mastic sealant
- Gasket
- Compressible foam
- Mortar

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

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

4. Matching available thin-walled GFRC manufacturing processes to increasing complexity of panel forms

The demand for more unique GFRC panels has been driven by the development of geometric software tools for the building industry (Pottmann, Asperl, Hofer, & Kilian, 2007). Current production methods for thin-walled elements in complex geometries cannot meet this demand so this must be resolved to advance thin-walled GFRC elements further. For free form building geometries such as the Heydar Aliyev Center, Baku, Azerbaijan (Bekiroglu, 2010) the scope for panel repetition was very limited because each individual thin-wall GFRC element shape and their fixing positions were defined explicitly. The production tolerances of the elements had to remain within span/1000 (CEN/TC 135, Juli 2009) to accommodate the tolerances in the secondary support structure. The connection brackets used for the

[2] When using mastic sealant, compressible foam or mortar to close the gap between adjacent panels, the aspect ratio between the depth of the thin-walled GFRC panel and the distance to the adjacent panel must be sufficient to accommodate the sealing material, with a typical minimum depth of 20 mm. Since thin-walled GFRC elements are produced typically with a thickness of 10-20mm, (if using the sprayed method) (Henriksen, Lo, & Knaack, 2015) (Fordyce & Wodehouse, 1983) (FIP State of art report, 1984) they require an edge return capable of accommodating the sealing joint between the panels. Thin-walled GFRC panels produced using the premixed method (Henriksen, Lo, & Knaack, 2015) (Fordyce & Wodehouse, 1983) (FIP State of art report, 1984) (ACI 549.2R, 2004) usually result in constant thicknesses of 40-60mm, which makes an additional edge return unnecessary for the purpose of closing the joint between the panels.

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

cladding on the Heydar Aliyev Center (See Figure 8) between the secondary support structure and the GFRC elements could accommodate a range of tolerances in the X, Y & Z planes, however the need for accurate manufacture of the GFRC element was paramount.

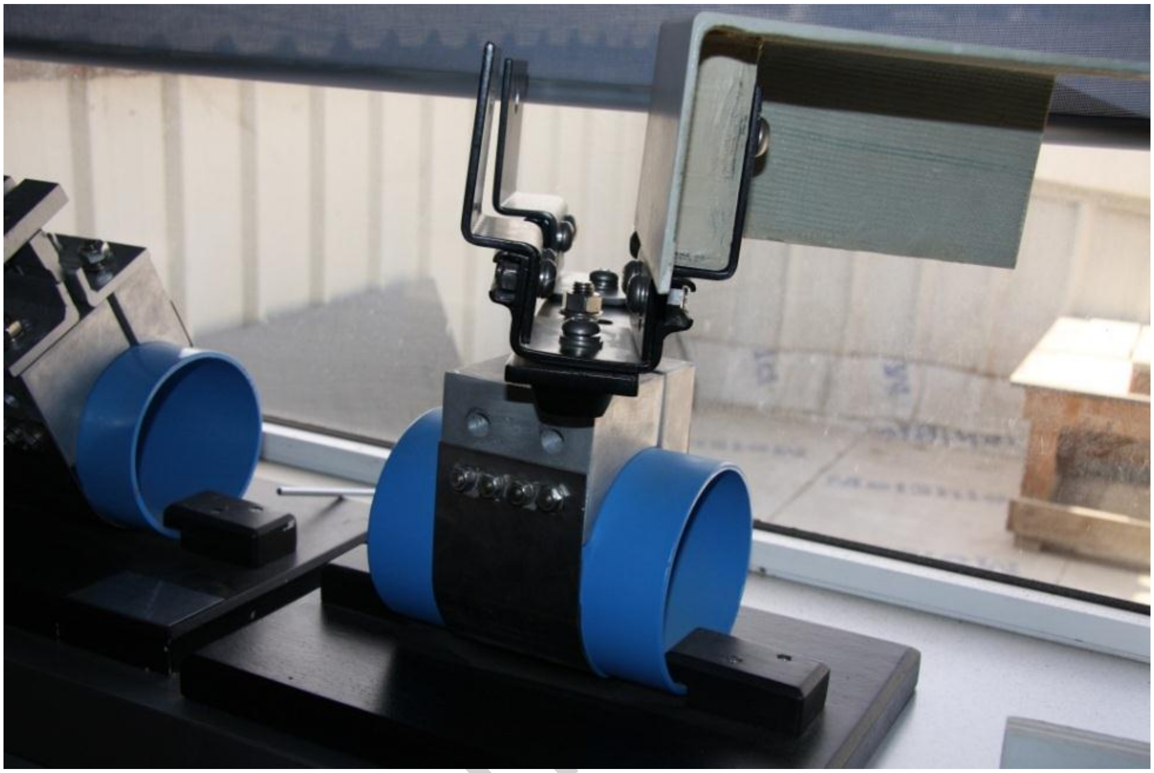


Figure 8 The connection between the secondary steel and the GFRP panels used on the Heydar Aliyev Center, which enables to accommodate tolerances between the secondray substructure and the complex geometry panels.

The possibility to adapt GFRC to complex geometry envelopes depends on the level of complexity as described in Table 2 and the requirements to the edge detailing of each thin-walled GFRC element. Each geometric category of thin-walled GFRC panel, (flat, single, double and freeform) may be divided into sub-groups dependent on the edge detailing and offsets in the panel.

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

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

Panel Geometry	Edge Detailing	Production Method		
		Sprayed	Premixed	Automated pre-mixed
Flat	Without edge return	✓	✓	✓
	With edge return	✓	✓	
	With Offset	✓	✓	
	Folded panel	✓		✓
Single Curved	Without edge return	✓	✓ (large radiuses)	✓
	With edge return	✓	✓ (uniform thickness)	*
	With Offset	✓		
Double Curved	Without edge return	✓	✓ (large radiuses)†	*
	With edge return	✓	✓ (large radiuses) †	
	With Offset	✓		
Free form	Without edge return	✓		*
	With edge return	✓		
	With Offset	✓		

Table 3 The limitations in GFRC production methods for the different geometric panels († Double curved premixed thin walled panels with an edge return are only possible in a double-sided mould. * Advances required in the automated premixed method to strive towards a fully digital complex geometry GFRC element process)

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

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

The automated premixed method, the premixed method and the sprayed method each have their different limitations depending on the level of geometric complexity, visual quality of the surface finish and the material strength. The geometric limitations for the 3 production methods are shown in Table 3. Table 4, Table 5 and Table 6 show how the different panels would look depending on the method by which they are produced. The automated premixed method has the most limitations in terms of geometric complexity, edge-returns and offsets. With the premixed method geometric shapes may be achieved if using a double-sided mould. This was technique was used to produce the LRT Station Canopy in Shawnessy, Calgary, Alberta (Perry & Zakarasen, 2005). However, in principle the premixed method is limited to panels with constant thicknesses if they have a complex geometry. The Sprayed method has few limitations in terms of the geometric shapes that can be achieved but are limited by the material properties (Henriksen, Lo, & Knaack, 2015) and the sprayed side of the panel has a rough unfinished texture.

5.1. Automated Pre-mixed method

The automated premixed method is predominantly used to produce flat GFRC sheets; however it is possible to form the sheets as they leave the production line when they are still in their "greenstate" (Henriksen, Lo, & Knaack, 2015) . The automated premixed Method has limitation on which geometric shapes can be achieved. Table 4 shows the panel geometries that can be achieved with the automated pre-mixed method i.e the Hatschek method (Hatschek, 1901) or similar automated premixed methods (Keer, 1990) (ACI 549.2R, 2004):

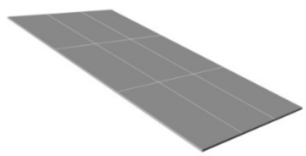
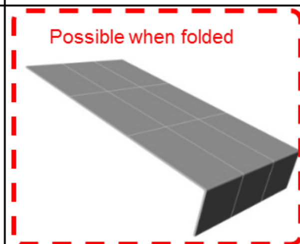
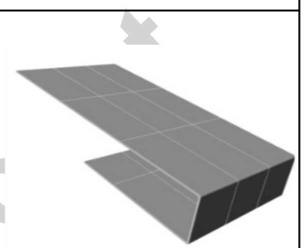
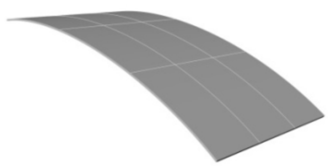
Automated premixed method	Without edge return	With edge return	Folded
Flat panels			
Single curved		*	*
Double curved	*	*	*
Freeform	*	*	*

Table 4 Thin-walled GFRC elements produced with the automated premixed method (* These panels will create a fold in the surface if they are folded)

The Hatchek method was designed to produce flat thin-walled Fibre reinforced Concrete (FRC) panels. However, an edge return can be created by folding the sides of the flat sheet, but the fibre orientation limits the bending strength of the folded corner. External mechanical fixings are necessary to prevent the edge return from breaking off. This folding technique allows a cube to be formed from a flat sheet of GFRC when the sides are folded in the concrete's "greenstate". It is possible to produce a single curved element without an edge return from the GFRC panel using the Hatchek method, including all the single curved cone geometries shown in Table 1. Single curved elements with an edge return would have to be folded in their "greenstate", however this would create ripples along the fold line and the upper surface of the single curved cone surface would no longer be in the same plane. Producing double curved and free form elements using the automated premixed method would also create folds in the main surface as shown in Figure 9. The uncured material from the automated premixed method would have to contract locally to accommodate the change in curvature; this is not possible with the Hatschek method (Hatschek, 1901) or the modified Hatschek method (Keer, 1990). Therefore the automated premixed method is currently limited to simple shapes.

5.2. Premixed

Thin-walled GFRC elements produced with the premixed method require double-sided moulds to create the intended shape. For geometries without an edge return such thin-walled elements are usually produced with a constant thickness over the entire panel. The panels are usually produced in thicknesses up to 60mm, which effectively present an edge return (Aubry, Bompas, Vaudeville, & Corvez, 2013). Thin-walled GFRC panels with a constant thickness of 40mm-60mm are very heavy and difficult to man-handle through fabrication, transportation and installation. Panels using the premixed method that need an edge-return or an offset require a two-part mould with a positive and negative element, where the premixed GFRC is injected into the mould cavity. To maintain an acceptable surface quality without too many blemishes, and to avoid balling of the fibres, it is necessary to have a very fluid GFRC mix (Henriksen, Lo, & Knaack, 2015). The most successful way is to inject the GFRC from the bottom of the mould with the visual surfaces facing downwards, and slowly fill the mould with GFRC.

Table 5 illustrates the variations of premixed thin-walled GFRC elements used in architectural complex geometry buildings. It shows the elements that can be produced with current techniques, most commonly milling the moulds with a 3-D CNC machine, (Feirabend, Emami, & Riedel, 2014).

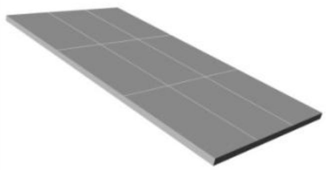
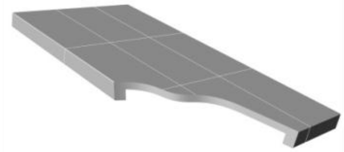
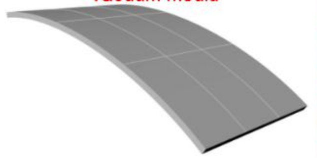
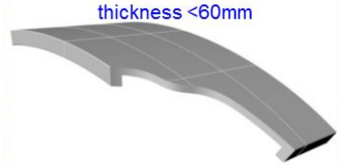
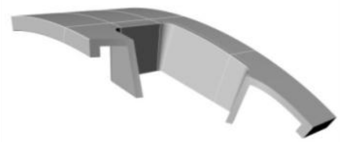
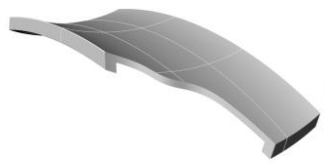
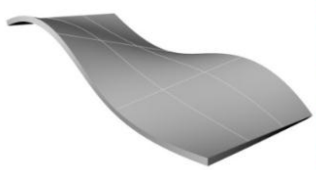
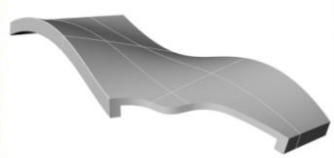
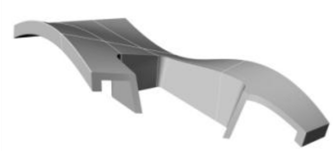
Premixed Method	Without edge return	With edge return	With an offset
Flat panels			
Single curved	Possible with double sided or vacuum mould 	Possible with constant wall thickness <60mm 	* 
Double curved			* 
Freeform			* 

Table 5 Thin-walled GFRC elements produced with the premixed method (* Panels are difficult to produce with the current production methods).

However, this method is slow and costly given the milling time required to make the moulds. It is also not cost effective to produce the many unique elements using the premixed method demanded by large buildings with complex geometry panels (Bekiroglu, 2010). Finally it is a challenge to completely mitigate air voids and blemishes in the surface using the premixed method, leading to a high rejection rate, (Fordyce & Wodehouse, 1983) (Rieder, 2013).

From the range of geometric types and shapes, only some of the edge returns and offsets shown in Table 5 are possible using current casting technologies. The flat shapes can be cast in a mould with a positive and a negative side, including those with an edge return and an offset. The panels produced for the King Abdullah Petroleum Studies and Research Centre in Riyadh, KSA (Bishop & Wilson, 2011), were finally produced using the sprayed method. For single curved, double curved and freeform panels, this is only realistic with a constant thickness, using a vacuum mould system (Behloul & Quidant, 2011), and is currently limited to larger radii and single curvatures. This method was used successfully for the Foundation Louis Vuitton in Paris, France (Aubry, Bompas, Vaudeville, & Corvez, 2013).

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

5.3. Sprayed method

Thin-walled GFRC elements produced with the sprayed method also require a mould, but the mould is simpler compared to the mould system necessary for a thin-walled elements produced with the premixed method. The sprayed method requires a negative mould to allow the intended shapes to be produced making it more cost effective and with a smaller rejection rate compared to the premixed method (Henriksen, Lo, & Knaack, 2015) (Fordyce & Wodehouse, 1983). The different types of elements that may be produced using the sprayed method are shown in Table 6. The flat elements without an edge return or offset are the most simple to produce. The production of a mould for double and free form shapes is complicated and is currently mainly only produced via milling of the mould in a CNC machine.

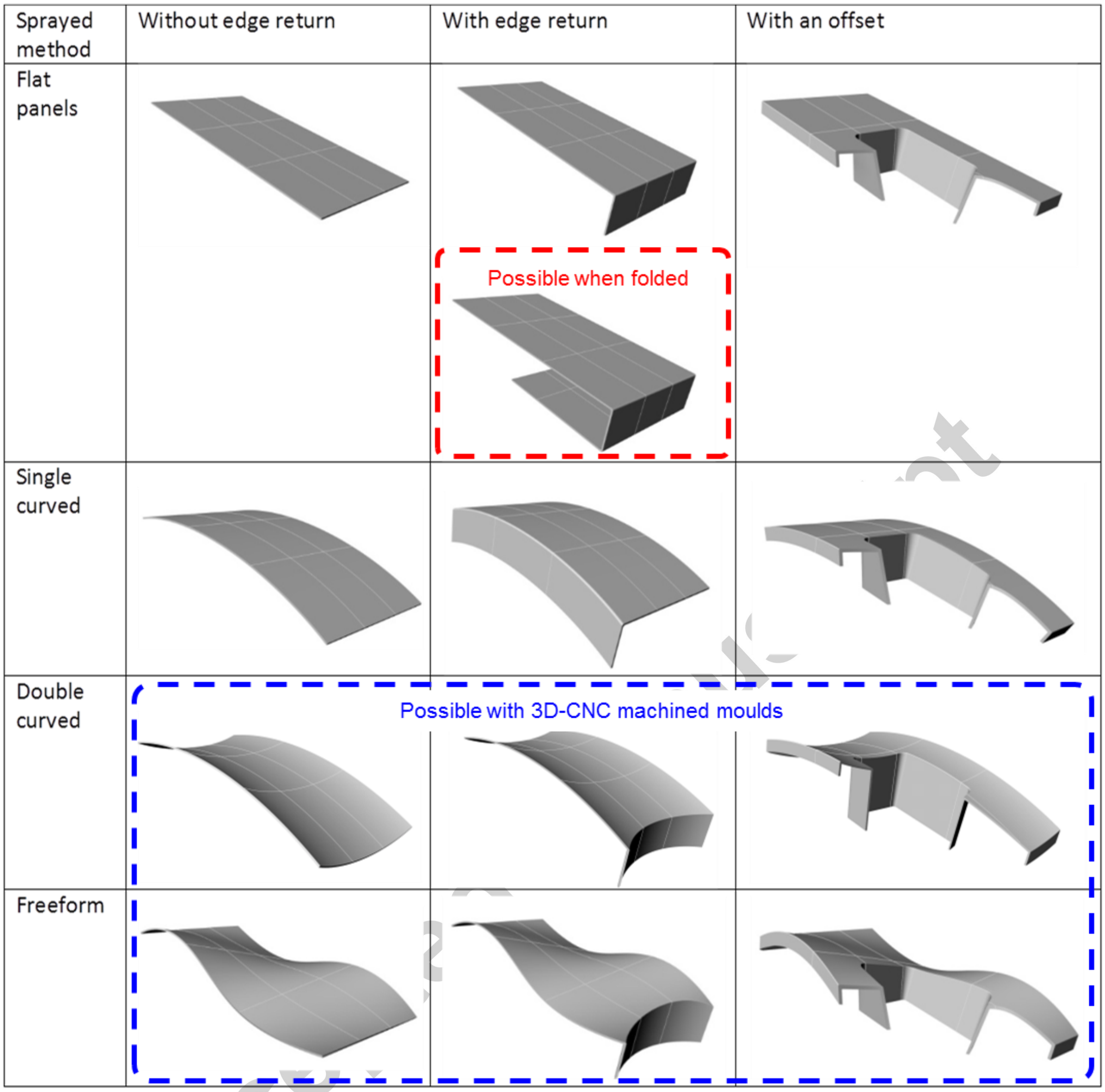


Table 6 Thin-walled GFRC elements produced with the sprayed method.

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

The sprayed method has the most flexibility in terms of achieving different shapes and offsets as shown in Table 6. Given the variety of possible geometric complexity, shapes, edge returns and offsets, almost all contemporary architectural buildings could be realised with an exterior GFRC rain-screen cladding. What currently prohibits this is the ability to produce moulds with the intended geometry and successfully casting the GFRC elements with an acceptable surface quality.

The sprayed method allows a face coat to be sprayed initially without any fibres (Henriksen, Lo, & Knaack, 2015) to minimize the number of air-bubbles and blemishes and visible fibres on the front surfaces of the thin-walled GFRC element. The disadvantages are that the back of the panel will have a rough appearance compared to a premixed panel produced with both a positive and negative mould. The spraying method is not the limiting factor because sprayed cementitious material relies on ordinary portland cement (OPC) or else the cement does not remain in place after it has been sprayed on the return edges of the sprayed mould or on the sides of the offset. Advancing the cementitious material for the sprayed method is difficult without using UHPC, however currently UHPC is to is similar to self-compacting concrete and would not stay in place on sloped surfaces when being sprayed, and difficult to apply via spraying for non-flat shapes. New technologies for spraying UHPC are being developed at the moment (Perez, Bernardi, Trucy, & Ferreira, 2015) (Peter, 2005), however they have not been used commercially. Current moulding systems are restricted and costly so to advance the application of thin-walled GFRC elements for complex geometries an innovative approach to the manufacture of the moulds systems must be developed.

6. Innovative approach to the manufacture of thin-walled GFRC

Thin-walled GFRC is currently typically fabricated with wooden moulds and predominantly using the sprayed method but such moulds can only be used for flat, single curved geometries and double curved geometries with large radii. For more complex geometries CNC machined moulds must be used, but are costly and take a long time to manufacture. These can only be reused for a limited number of cycles, increasing the need for additional moulds, so a new method has been explored that could potentially reduce the time and cost to produce moulds for complex geometry GFRC. Recent developments have focused on making flexible tables able to accommodate the demand for ever-changing geometries by allowing a digitally generated shape to be formed, (Raun, 2011) (Schripper, 2010). To prevent shrinkage cracks forming during de-moulding, and to maintain colour consistency of the thin-walled GFRC, it needs to remain in the mould for the full curing period. When testing a flexible table at an automated premixed production line shown in Figure 9, it became apparent that the flexible table alone would not resolve the demand for the number of moulds necessary to produce many different unique panels at the same time. Therefore the flexible table process was advanced to create moulds able to generate the intended form when the final shape of the panel, with edge-returns and offsets, had been determined. This innovative new mould casting system will enable many unique shapes to be fabricated while still utilizing the costly flexible table to its full potential, all within a 30 min cycle.

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

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

The first step is necessary to transform the design intent into a buildable solution, since many initial free form shapes used in architecture only showcase the initial layer of the surfaces and not at this stage in the design development solving the joint width and the offset of the panels in terms of the edge-return and the offset openings (as shown in Figure 3). The detailing between the top surface and the angle of the edge-return is paramount for the fabrication and the complexity of the production of free form panels. The second stage forms the correct geometry on the flexible table and projects the correct geometry of the panel on the table, allowing the correct angle of the new mould to be formed. The third stage is the new casting method for the new mould, using a fast curing expandable material. Ideally this would be an sustainable organic material, with a low environmental impact. Initially a self expanding foam was used as shown in Figure 10. Stage two and stage three forms the basis of the new innovation. The main reason for introducing these additional steps is that the flexible tables are unsuitable for the economic mass production of thin-walled GFRC elements as they are very costly, and many tables were needed to produce element for projects as the Heydar Aliyev Center. Figure 9 shows a flexible table with a freeform shaped top surface. A thin-walled GFRC panel has been placed on the table, still in its “greenstate”.

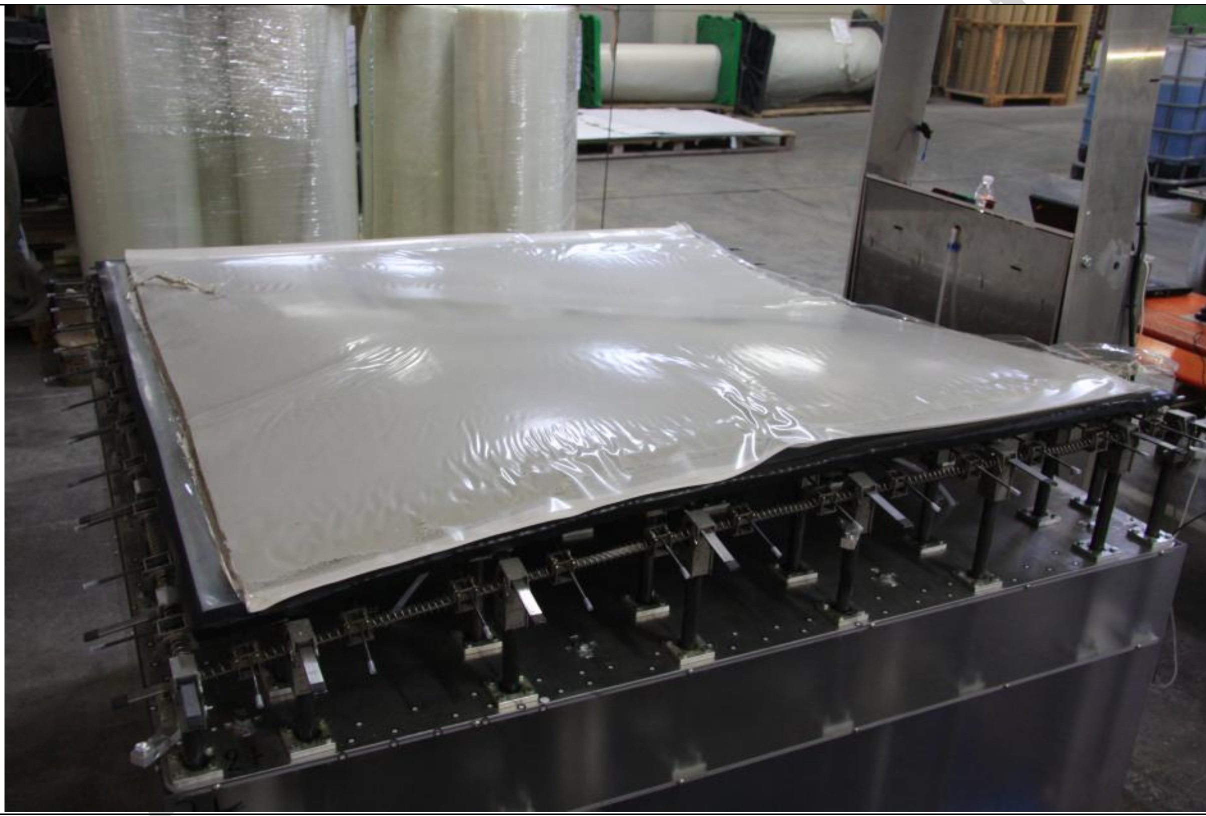


Figure 9 Testing of a thin-welled GFRC panel produced with the automated premixed process on a flexible table. The flexible table is positioned in a freeform shape

The proposed new approach adds an additional step in the process to allow the full benefits of a flexible table to be realised so that the cast mould can be used in the production of the full range complex geometry GFRC elements as shown in Figure 10.

Figure 10 The proposed new approach which adds an additional step bewteen the flexible table and the casting of the GFRC element.

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

Conclusion

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

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

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

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

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Highlights

We have identifies the current architectural and aesthetic requirements of thin-walled GFRC elements and maps their increasing complexity, from 1-D to 3-D, to the limits of the most appropriate production method.

It inform guidelines for the future design development of thin-walled GFRC and enable an innovative approach to further advance the moulding techniques for thin walled GFRC elements for complex geometry building envelopes.