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

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ABSTRACT

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

1. Introduction

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

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

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

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

This moulding technique uses two layers of polyurethane foam with a high density foam (37–38 kg/m^3) at the surface to minimize damage from casting, and a low density foam core (15–16 kg/m^3) below, where merely support is needed. It also allows the mould to be reused for more casting cycles. This not only allows the system to be re-used but the lower overall density of the foam incurs less cost. This is more sustainable than current CNC milled foam materials where the form material has a constant density.

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Furthermore the new moulding technique would allow integration into an automated premixed method for a more streamlined fabrication process for thin-walled GFRC elements. An overview of the key problems and limitations in the production of complex geometry thin walled GFRC elements with offsets and edge returns are examined to inform the production capabilities required by any new moulding system.

2. State of the art GFRC elements

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

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

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

3. Existing moulding systems for GFRC

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

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

During the research for new mould systems it became apparent that the cost of the current moulds was an important part of the overall cost of a complex geometry GFRC building. However, current indicative costs for the different mould techniques are either not available or out of date. In this research 3 established GFRC manufactures in Europe, Denmark [23], Germany [24] and the UK [25], were interviewed to determine the approximate cost of current mould production. The costs were indicative and could vary from continent to continent. The costs shown in Table 1 are for single sided moulds so for double sided moulds the cost would have to be doubled. Such current indicative costs will be used for guidance when estimating the cost of producing complex geometry GFRC panels.

Existing mould systems that are able to produce complex geometry thin-walled FRC elements can be divided into the following categories, as shown in Table 1, [24–26]:

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

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

Existing moulding systems for thin-walled GFRC are traditionally made out of wooden moulds or bespoke steel moulds if much repetition is required [27]. However, the wooden moulds are usually only available for flat or single curved geometries with large radii ($r > 0.5$ m) [28]. For double curved wooden moulds the wooden surface sheet must be sufficiently thin to enable ease of forming. This technique is not cost effective for the production of thin-walled GFRC with little or no repetition. The range of current mould types is illustrated in Figs. 1–8. Fig. 1 shows a single curved sprayed GFRC element with a constant radius. Fig. 2 shows a single curved wooden mould with a cone like geometry [8], and the mould is being prepared for curing of the sprayed GFRC.

Rubber moulds are an alternative method of casting thin-walled GFRC and are used for GFRC elements with special features, making very fine and detailed surfaces possible. To produce a rubber mould an initial "negative" mould must be manufactured to produce the "positive" rubber mould, which, again is not cost effective unless there is significant repetition. Building more unique thin-walled GFRC panels, with little or no repetition requires a different moulding system with rubber moulds to make textured surfaces possible due to the casting techniques of the rubber moulds and is difficult to achieve with other mould types. Fig. 3 shows a rubber mould with a wooden texture.

Closed cell extruded polystyrene foam moulds are another method of producing moulds since the mould material is cheap. For single curved geometries [8] the polystyrene foam can be cut easily with a computer guided hot wire cutter to give the intended shape [29]. This method is limited by the ability of the hot wire cutter to only produce a positive mould. Fig. 4 shows a polystyrene mould used for single curved thin-walled GFRC produced with an automated premixed process. The moulds have been cut with a hot wire cutter but are limited to ruled surfaces. It is possible to create complex and very precise shapes using a robot arm together with a hot wire cutter [30].

Fig. 5 shows a robot guided hot wire cutter, that be used to make high precision moulds.

CNC milled moulds are used currently for complex shaped GFRC elements and can be produced using plastics, foams, wood or metals. Such moulds are costly compared to other moulding systems, however, currently there are few alternatives. The milling process incurs significant material wastage and the size of the moulds is limited by the size of the milling machines. CNC milled moulds can be used for more complex forms and it is

Fig. 1. Single curved sprayed GFRC element on a wooden mould.

Fig. 2. Wooden mould with a double curved surface. The double curvature is possible because of the big radii.

Fig. 3. Flat rubber mould with a texture finish.

possible to make a mould with recesses that can be used to cast almost any shape. The main limitation of the CNC milling process is the time it takes to mill the surface and the limited quality of the milled surfaces [31] as shown in Figs. 7 and 8.

Table 1
Existing mould system to produce then walled GFRC.

Mould type	Labour intensity	Material cost and labour costs	Mould production time	Reusability[a]	Comments
Wooden moulds (limited to single curved and large radii (r > 0.5 m) double curvature)	medium	Material 25€/m^2; Labour 40€/h	2–4 h/m^2	1–20 times	Sometimes a structural calc. for a timber mould is also required (concrete-pressure and weight). This adds additional cost
Steel moulds	High	Material approx. 50€/m^2	5–8 h/m^2	20–500 times	Steel moulds are used when it is required to have a seamless appearance, largest size 400 × 600 cm
Rubber moulds	High	Material 80–200€/m^2	3–5 h	10–50 times	Must be applied to a timber mould. Limited sizes
Polystyrene foam moulds, wire cut	Low	Material will be calc. in m³ foam. approx. € 30,–/m³	1 h	5–30 times	Standard Polystyrene foam-block is 120 × 120 × 500 cm, Significant waste
3D computer numerical controlled (CNC) milled moulds (Foam, Plastic)	Low	300–400€/m^2	5–10 h	5–10 times	The moulds are typically made from foam or plastic. Timber or metal alternatives can also be used. The quality of the mould depends of the quality of the foam or plastic. Limited sizes
Flexible tables with pistons	Low	High machine cost	20 min	Motors 10,000 times Surface 100–500 times	Limited sizes approx. 1 m × 2 m
Flexible tables with actuators and membranes	Low	High machine cost	5 min	Motors 10,000 times Surface 500 times	Limited sizes currently approx. 1.2 m × 1.2 m

[a] Depends on the mould geometry.

Fig. 4. Single curved polystyrene mould.

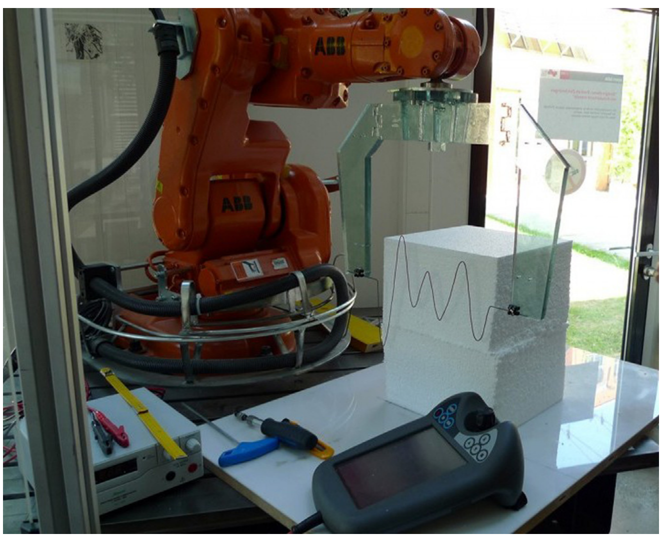

Fig. 5. Computer controlled hot wire cutter.

Fig. 6. Finished art project, where the GFRC elements has been cured on hot wire cut polystyrene.

Fig. 7. 3 Axes CNC machine.

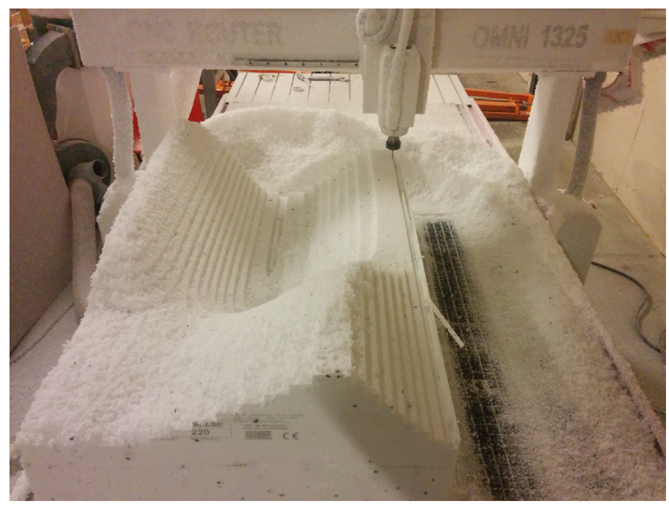

Fig. 8. Concrete mould milled by a CNC machine.

Such a time consuming milling process increases the cost of milling a mould compared to those made from timber so alternative moulding systems are being sought [32]. The new proposed mould system for complex geometry thin-walled GFRC panels [8] is one such alternative to using CNC milling of moulds.

3.1. Digital moulding technique for complex geometry GFRC

The early development of discretized double curved concrete was pioneered by the completion of the Sydney Opera House [33] and Heinz Isle's development of hyperbolic concrete shells [3]. Renzo Piano followed these developments by suggesting an alternative apparatus to make double curved surfaces [34] but limitations in technology at the time halted further progression. More recently the development of digital parametric design has evolved to a level where it is possible to digitally determine shapes and curvatures [35,36,29]. This led to digital flexible tables that could be automatically actuated to meet intended shapes but they were limited to low rates-of-change in curvature. The Sailing industry was the first to introduce a digital flexible table for the production of fixed sails for racing yachts [37]. Digital flexible table technology for the architectural industry was introduced in 2007, aimed at double curved glass production [38] but because the process of bending glass required high temperatures, the technology at that time was not ready for the production of such double curved glass. Subsequent tables, more suited to double-curved forms [39], were then proposed for 3 dimensional concrete. Such digital flexible tables can be divided into two categories:

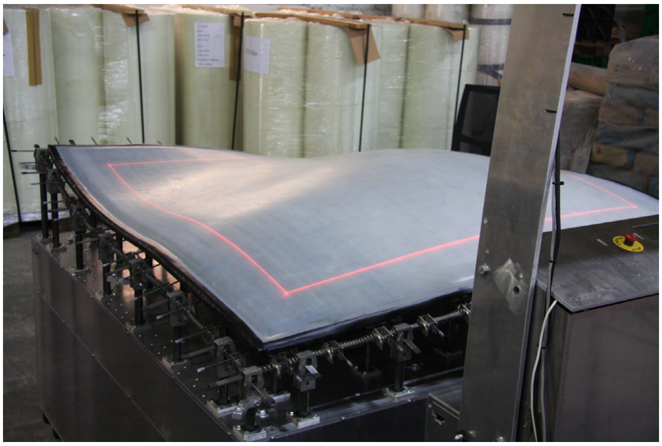

Fig. 9. Digital flexible table with actuators and membrane positioned to give a freeform surface.

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

Digital tables based on piston-actuated surfaces were comprised of small pistons but could not form a continuous surface, have been proposed [40,41], so are not suitable for "prestigious" concrete surfaces. A digital table using pistons with a membrane was proposed in 2010 [42], and had the ability to make offsets in the surface, however, the profile of the top of pistons could still be seen through the membrane and became visible on the concrete surface.

Digital flexible tables with actuators and a surface membrane for freeform concrete surfaces were proposed in 2006 and further developed in 2010 [39,21,43] and could be computer-controlled. The surface was able to form continuous shapes by manipulating support points for casting various materials on the surface. Such a system is shown in Figs. 9 and 10.

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

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

- Minimum 24 h curing time of the concrete on the table.
- The inability to create offsets in the surface.

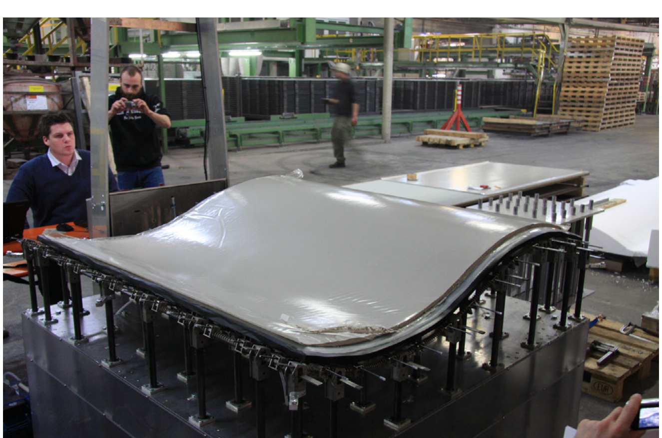

Fig. 10. Automated premixed concrete panel placed on the digital flexible table in a single curved profile while curing.

- Accuracy (± 2 mm) of the table to meet the intended continuous surface.
- Limited to radii of 0.5 m and a maximum panel depth of 0.4 m.
- High cost of the table.
- Limited durability of the membrane during multiple cycles.

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

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

4. New moulding system for premixed GFRC

During the development of a new mould system it was important to understand the limitations and barriers imposed by existing systems. The main problem with mould systems using premixed GFRC for complex geometries is that they require a double sided mould to enable the concrete to flow into all parts of the mould. That mould also has to be vibrated to release trapped air-bubbles from the concrete mix. The main challenge in developing the mould system was to find a way to allow for an edge-return in the mould system. The edge-return is an essential aesthetic feature in contemporary architecture. On the Fundation Louis Vuitton in Paris [28,22] this was solved by allowing a constant (60 mm) panel thickness and to form the panels in their "greenstate" [8] using a vacuum system to ensure the concrete did not flow away from the corners. However, the system relied on ruled single curved geometries and was unsuitable for double curved surfaces with small radii and freeform surfaces.

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

Fig. 11 illustrates the method to produce the positive mould for the new moulding system. The surface of the flexible table is highlighted in blue and the positive foam mould is indicated in yellow.

Fig. 12 shows how the positive mould is produced. The green surface shows the repositioned surface of the flexible table. The black flexible band shown on the surface is used to create the

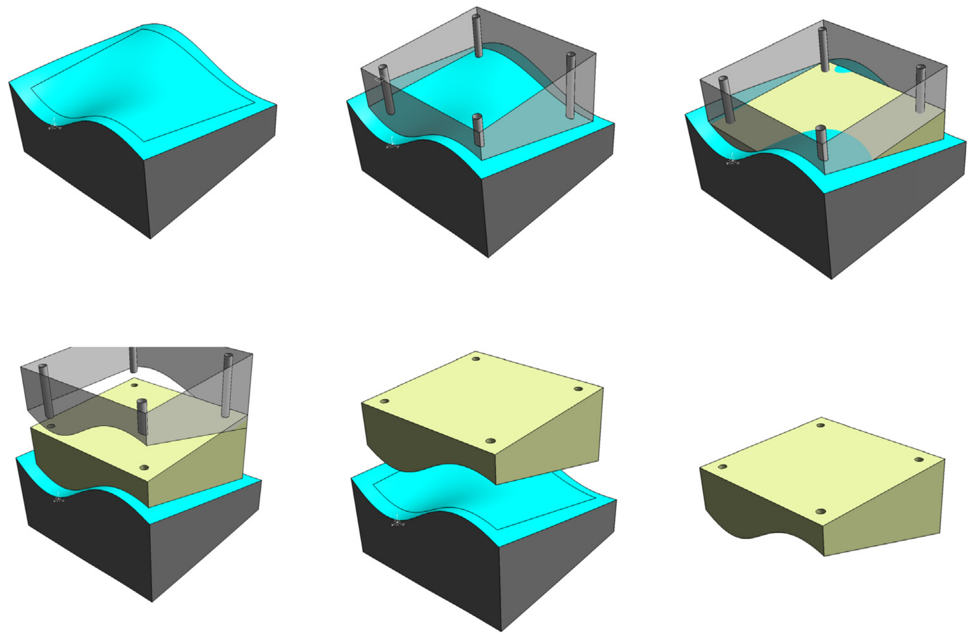

Fig. 11. New mould system production of the negative mould. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

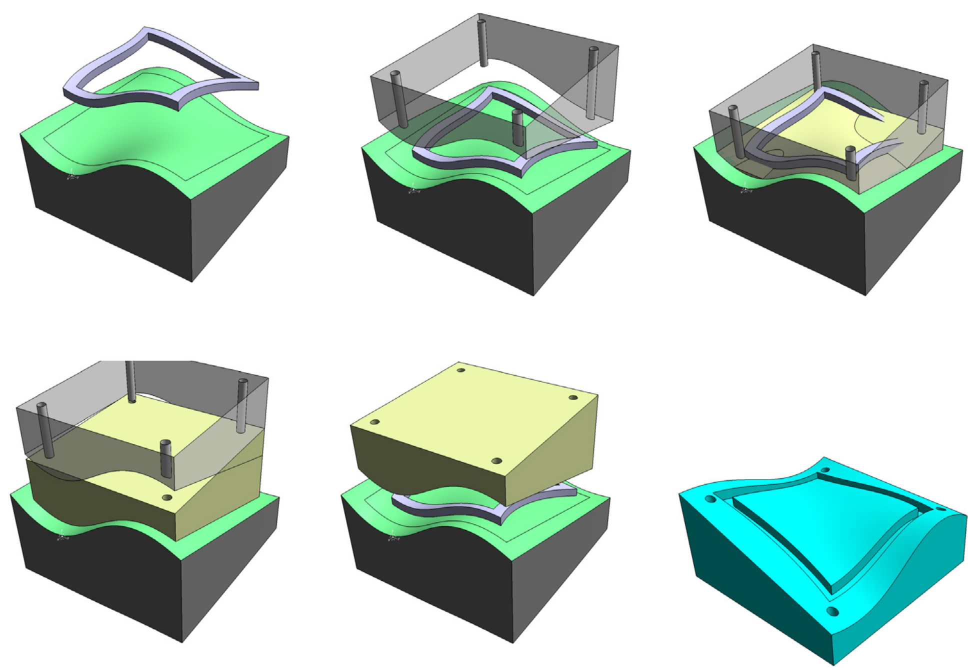

Fig. 12. New mould system production of the positive mould. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

offset in the negative mould surface. The blue part shows the negative mould with the offset.

Fig. 13 shows how the negative part from Fig. 11 is assembled with the positive part from Fig. 12. The black flexible band acts as a spacer and provides a void between the 2 mould elements.

When the 2 parts are assembled it is possible to cast concrete between two elements, as shown in Fig. 14 with the first prototype cast using the new mould system.

The foam mould on the left represents the negative mould, and the foam mould on the right represents the positive mould. Fig. 14 shows it was possible to create a continuous double curved surface with an edge return using the new mould system.

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

The advantages of the proposed mould system are that it is cost effective and fast to manufacture compared with the other mould systems described in Table 1. The production speed using the foam casting technique allows the desired surfaces to be created in less than 5 min when compared to CNC milling of moulds, representing a significant reduction in production speed, and waste of materials.

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

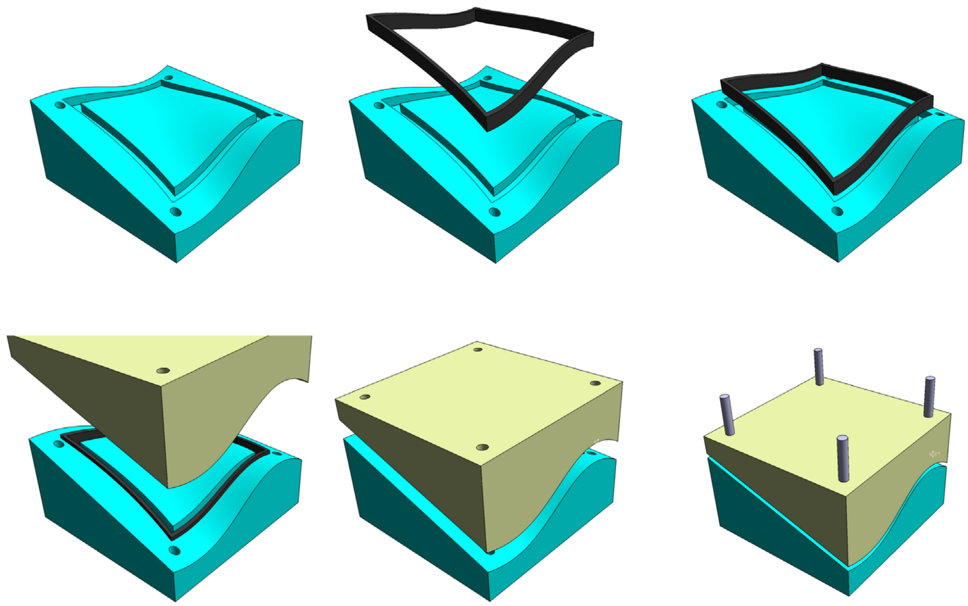

Fig. 13. New mould system assembly of the positive and the negative mould parts.

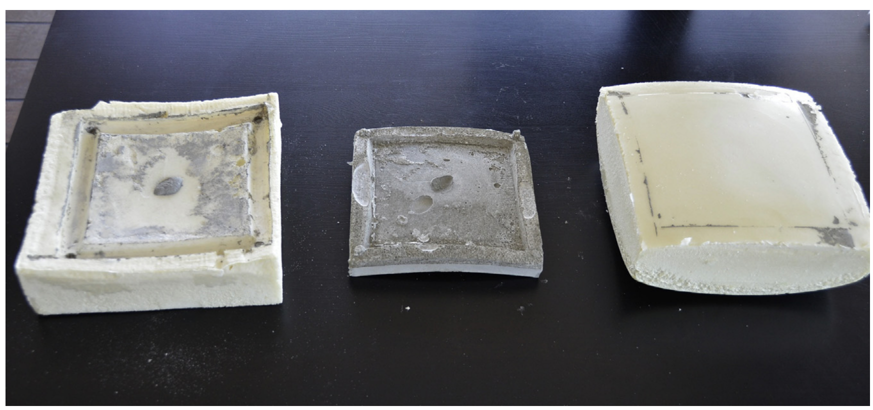

Fig. 14. The first cast (23 cm × 23 cm) prototype utilizing the new mould system.

Table 2 shows the different types of mould systems and their limitations in relation to the complexity of the thin-walled GFRC elements, and the possibilities of the new moulding system.

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

5. Process description

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

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

1. Generating a geometric shape using CAD software, and subdivide the shape into single elements.
2. Positioning of the flexible mould in the correct freeform position, using a predefined shape developed from 3D software. (The first position creates the positive side of the finished foam mould).
3. Positioning of form-adaptable boundary walls to the flexible mould (Fig. 15).
4. Positioning of silicone blocks to form the edge-return in the cast foam mould.
5. Casting of the foam inside the form adaptable boundary walls.
6. Curing of the positive side.
7. Repositioning of flexible mould in the correct free-form position, using a predefined shape developed in 3D software. (The second position creates the negative side of the finished foam mould).
8. Positioning of form-adaptable boundary walls on the flexible mould.
9. Positing of silicone blocks to form the edge-return in the cast foam mould.
10. Casting of the foam inside the form-adaptable boundary walls.
11. Curing of the negative side.
12. Assembly the positive foam mould side with the negative foam mould side.
13. Mixing the concrete in a vacuum mixer [45] to prevent air bubbles.

Table 2
The different types of mould systems and their limitations in relation to the complexity of the thin-walled GFRC elements, and the possibilities of the new moulding system.

Panel geometry	Edge detailing	Mould systems				
		Wooden moulds	Flexible table with pistons[a]	Flexible table with actuators and membrane[b]	CNC milled moulds[c]	New mould system
Flat	Without edge return	✓	✓	✓	✓	✓
	With edge return	✓ (Uniform thickness)	✓ (Sprayed)	✓(Sprayed)	✓	✓
	With Offset	✓			✓	✓
Single Curved	Without edge return	✓	✓ (Large radiuses (R > 0.5 m))		✓	✓
	With edge return	✓ (Uniform thickness, large radiuses)	✓ (Uniform thickness, large radiuses)	✓ (Uniform thickness, large radiuses)	✓	✓
	With offset				✓	✓
Double Curved	Without edge return	✓ (Large radiuses)	✓	✓	✓	✓
	With edge return	✓ (Sprayed)	✓ (Uniform thickness, large radiuses)	✓ (Uniform thickness, large radiuses)	✓	✓
	With offset				✓	✓
Free form	Without edge return		✓	✓	✓	✓
	With edge return				✓	✓
	With offset				✓	✓

[a] With the current development in piston tables it is not possible to achieve a continuous surface.
[b] Curing time reduces the usage of the flexible tables.
[c] Surface quality of the CNC milled moulds is still problematic.

Fig. 15. Form-adaptable boundary wall equipment, to be placed on the flexible table.

14. Applying a release agent on the mould surface to allow for easy de-moulding.
15. Casting the premixed concrete in the finished foam mould using another vacuum system to remove any remaining air bubbles in the concrete.
16. Curing of the concrete for 28 days under controlled conditions.

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

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

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

6. Further advances

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

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

To exploit the benefits of an automatic premixed method the new mould system would utilize the development of the new moulding system adapted to the sprayed method.

7. Conclusion

The manufacture of freeform thin-walled GFRC elements has been limited by current production techniques. This paper evaluates the key problems and limitations in the production of complex geometry thin walled GFRC elements with offsets and edge returns.

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

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

The new process described also permits the fabrication of complex geometry thin-walled GFRC elements using more cost effective large scale production methods. This offers a solution that bridges the gap between the limited capabilities of current solutions and the architectural aesthetic requirements of good surface quality and the option of having an edge-return with the same surface quality as the front surface. A patent application for this innovative method of producing thin-walled GFRC was submitted in 2013 [48].

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

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