Advancing the architectural application of complex geometry GFRC

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Abstract

Glass Fibre Reinforced Concrete (GFRC) has been developed over the last 50 years into the material it is today. GFRC is mostly used as a cladding material and to a lesser extent for structural elements. This paper examines the challenges of using freeform thin-walled GFRC elements in the design and fabrication of a self-supporting artwork. The initial conceptual design of the artwork using the latest parametric software tools is described. The structural analysis of the artwork is presented showing the feasibility of creating a structurally self-supported freeform GFRC structure. In the structural analyses the main stresses in the structure and the deflections are calculated and compared to the allowable stresses. Two models were evaluated; a fully monolithic model, which would assume the artwork being cast as one element, and a discretized model assuming the artwork comprised of small elements, joined using structural connections. The analysis showed that the discretized model had stresses below the maximum allowable stresses, however, its feasibility depended on the connection between the elements. It was necessary to develop these connections further.

Keywords: GFRC, complex geometry, flexible moulds, casting moulds, sprayed Method

INTRODUCTION

Since the introduction of Glass Fibre Reinforced Concrete (GFRC) (1) (2) (3) (4) in the 1970s and with the experience from the first monolithic concrete shell structures made by Torroja (5), Candela (6), Isler (7), Nervi (8) and Schlaich (9), solutions to engineering a self-supporting complex geometry prefabricated concrete shell structure has been a vision.

In this paper a self-supporting prefabricated complex geometry GFRC shell was designed using parametric software tools and the shell structure analysed, and possible connection details between the individual panels suggested.

This paper seeks to showcase the potential of creating a complex geometry shape utilising thin-walled GFRC elements using the latest digital technology to generate the shape, combined with a new moulding technology, based on a digital flexible table (8).

THINKING SPACE/ TESTING SPACE

The geometric shape was created by the Architect Ben Allan in corporation with the Author for the design competition for an Artwork in Arup HQ,London 2015 (9). The Artwork was based on the Idea of Antoni Gaudi (10) and Heinz Isler (7), utilizing a catenary system to produce a geometry which will always be in compression.

The Thinking space / Testing space is shown in Figure 1

Figure 1. *Rendering of the proposed Artwork, Thinking space / Testing space*

The design of the Artwork was based on 96 free form thin-walled GFRC elements; each element was approximately 1,2m x 1,2m. The thin-walled GFRC elements were connected together to form the self-supporting structure. The idea behind the Artwork was to show what was currently possible when the ideas of Antoni Guadi and Heniz Isler were combined with the latest geometric design tools and digital fabrication methods. The suggested height of the Artwork was to be 12 meters, however, before the final height could be determined the detail analysis and testing of the elements and the connections needed to be undertaken.

PARAMETRIC MODEL OF COMPLEX GEOMETRY GFRC SHELL

The Artwork is a hyperbolic form which is subdivided into elements of 1.2m x 1.2m. The form was generated using a parametric model, developed using a Grasshopper Script for Rhino 5.0. An image of the script is shown in Figure 2.

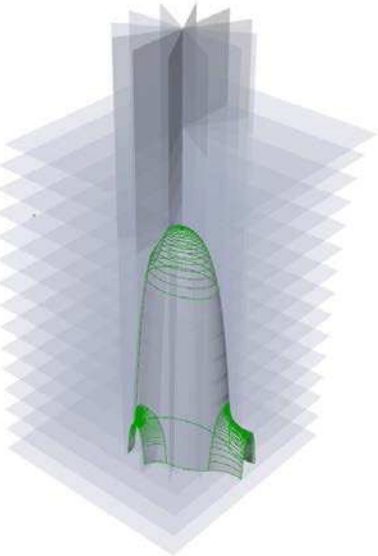

Figure 2. *The parametric model used to define the elements in the artwork.*

The parametric model allowed the shape to be divided in equal sized elements except around the entrances at the bottom of the Artwork where the changes in curvature were too great to allow equal spaced elements. The parametric model allowed the height of the model, and also the number, and size of the elements, to be changed. This enabled the artwork to be scaled into bigger or smaller elements. Different versions of the Artwork are shown in Figure 3.

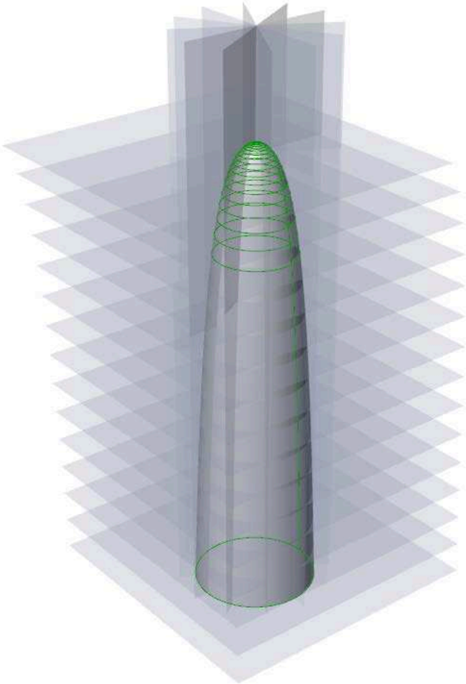

Figure 3. *An alternative form of the artwork.*

As part of the design development the final height of the model had to be developed, based on the structural capacity of the final artwork. The determination of the structural capacity was a combination of the connection ability to transfer loads, the local stability of the individual elements and the fabrication and installation tolerances of the panels, since too large tolerances would create eccentricities that generated local moments, which needed to be accommodated in the connections.

STRUCTURAL USE OF THIN WALLED GFRC, CONNECTION DETAILS.

Structural use of GFRC for complex geometry buildings was first proposed by Jurg Schlaich for the Stuttgart garden pavilion in 1977 (6), where 7 identical shells were cast in-situ on a wooden frame work, and then connected. Each shell element was monolithic and hyperbolic in form. The proposed Artwork is based on single elements being connected to form a free form shell structure. An analysis of the Artwork has been made to determine the structural behaviour of the shell. Figure 4 shows the initial structural model of the Artwork, with each 1.2m x 1.2m element.

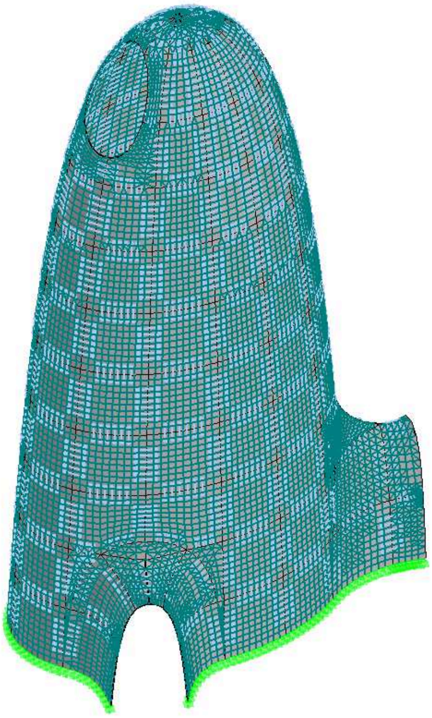

__Figure 4 .__The FEM model of the Artwork

The Structural model consisted of shell elements. For sprayed thin-walled elements ordinary Portland cement mixed with Glass fibres was assumed. The material properties for the sprayed GFRC used in the analysis is shown in Table 1.

	Units	Spayed GFRC
Density	kN/	19-21
Compression strength	MPa	50-80
Elasticity modulus	GPa	10-20
Impact strength	MPa	10-15
Poisson ratio		0.24
Limit of proportionality (fy)	MPa	7-11
Moment of rupture (fu)	MPa	21-31
Tensile strength	MPa	8-11

***Table 1** Material properties for sprayed thin-walled GFRC*

The Artwork was been analysed for 2 different structural situations:

1. Full monolithic shell structure.
2. Discretized shell structure, consisting of small elements connected in the corners.

The two models were analysed separately a then compared to enable the two structural models to be compared.

The monolithic shell structure was modelled with a GFRC wall thickness of 10mm. The material properties used in the analysis are shown in Table 1. The support condition of the monolithic shell structure was modelled as simply supported, reflecting a ring beam at the bottom of the structure. The structural model of the full monolithic structure is shown in Figure 5.

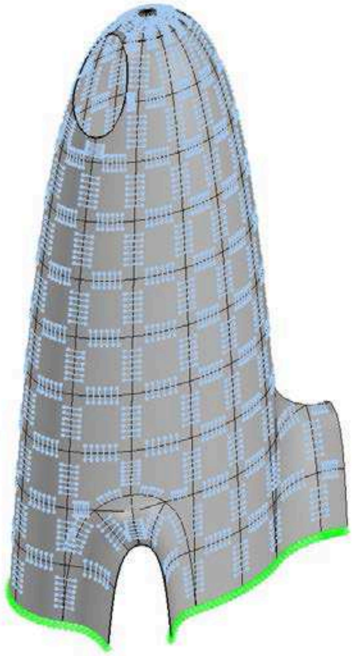

Figure 5 *FEM model of the monolithic shell structure*

In this case the structural system was a shell acting as a monolithic shape composed of curved panels. The majority of the panels were 1.2m x 1.2m with thickness equal to 10mm. The boundary conditions of the panels considered restraints for all 6 DOF (three rotational and 3 translational). At the bottom edge of the structure the panels were considered to be supported linearly with pinned supports, i.e. releases only in all 3 rotational restraints. The analysis of the monolithic structure was performed with commercial FEA software considering small deformations (linear elastic analysis). The mesh generated was a combination of quadrangular and triangular shaped finite elements of 100mm dimensions. A non-linear analysis and the fracture mechanical behaviour are disregarded in the initial analysis.

The structure was intended to be installed in an interior space; therefore the loading on the structure was reduced to an internal wind-load of 0.3kN/.
For the monolithic structural model the maximum stress and maximum deflection was analysed. The general stress was below 6MPa, however there were local singularity problems given the change in curvature at the entrances to the Artwork. The maximum deflection was calculated to be 12.7mm, which was span/950 for a cantilever structure.

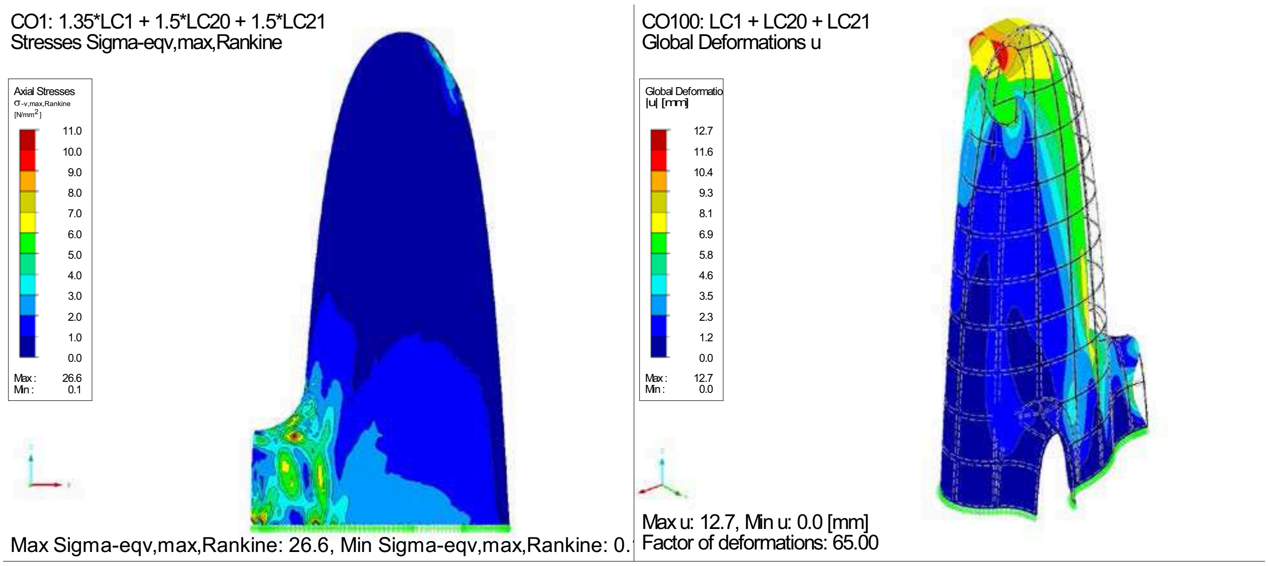

***Figure 6** The maximum combined stresses and maximum deflection for the monolithic shell structure.*

The discretized shell structure was analysed in the same way as a monolithic shell structure. The calculated stresses in the modelled connections were calculated to approximately 10MPa, the discretized shell structure also had problems with singularities at the openings, which were generally disregarded. The maximum deflection of the discretized shell structure was calculated to be 32.3mm, which is span/370 for a cantilever structure.

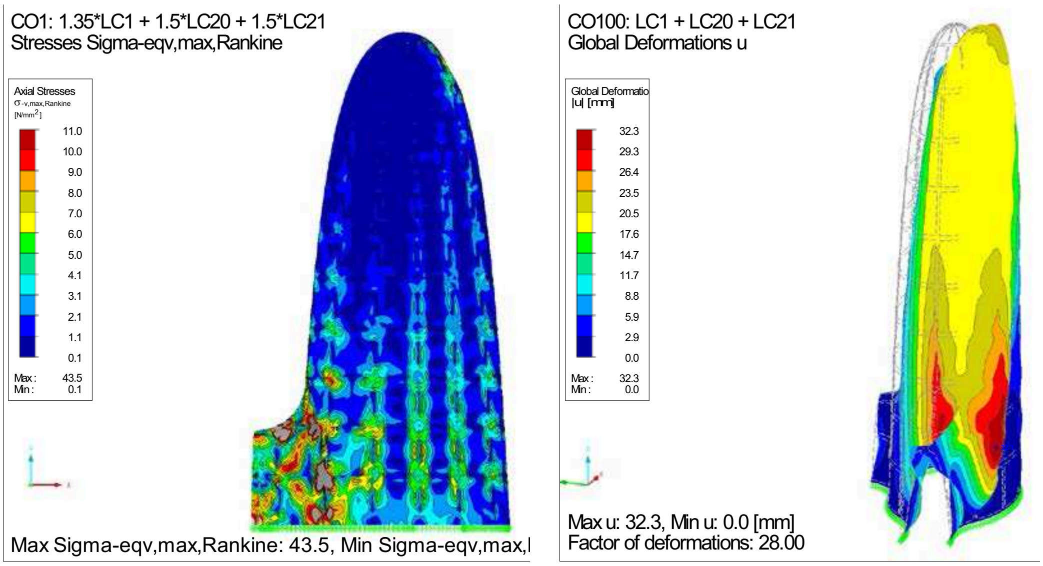

***Figure 7** The maximum combined stresses and maximum deflection for the discretized shell structure.*

The stresses for the 2 different models with the 0.3kN/ area load applied to one side of the model and the dead load combined using Euro-codes was compared in Table 2.

	Monolithic model	Discretized model
Maximum stress	6 Mpa (26 MPa)*	10 Mpa (43 MPa)*
Maximum deflection	12.7 mm	32.3mm
* The maximum calculated stress in the model reflects singularities in the area around the openings at the bottom.		

Table 2 *The maximum stresses and deflections for both models.*

The stresses in the discretized model were close to the maximum limits of the tensile strength of the sprayed GFRC. Therefore thicker elements were considered at the base of the Artwork.

The forces in the connections for the discretized shell structure were calculated by using a simple approach where the moment from the simple cantilever structure was calculated to 108kNm. The maximum tensile force was calculated to 36kN, assuming a distance between the 2 main sides of 3m. Due to the geometry, only 4 of the middle panels would be able to transfer the load. If undercut anchors were used as the fixing method, then the number of fixings in each panel needed to be 6 No. assuming each fixing could accommodate a design shear load of 1.6kN.

However, for the connection detail, 3 different connections were considered. The first connection was a bolted connection with latch plates. The Bolt holes were close fit holes that could transfer the forces directly from one element to the other. The connection is shown in Figure 8.

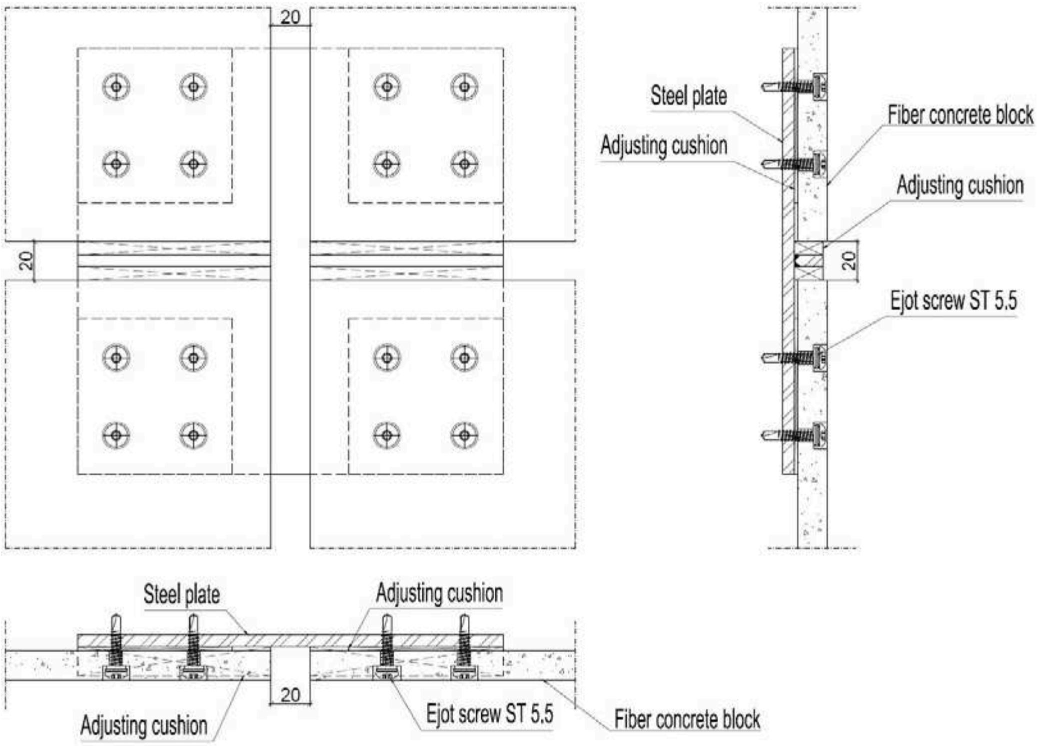

Figure 8 *A simple bolted connection with a predrilled hole in the GFRC plate.*

The connections connected four elements together in each corner.

The second proposed detail was a typical connection detail used for sprayed elements, comprising a stainless steel angle cast into the GFRC element. This connection differed from Connection detail 1 and 3 because it could transfer small moments in the connection. The cast-in connection is shown in Figure 9.

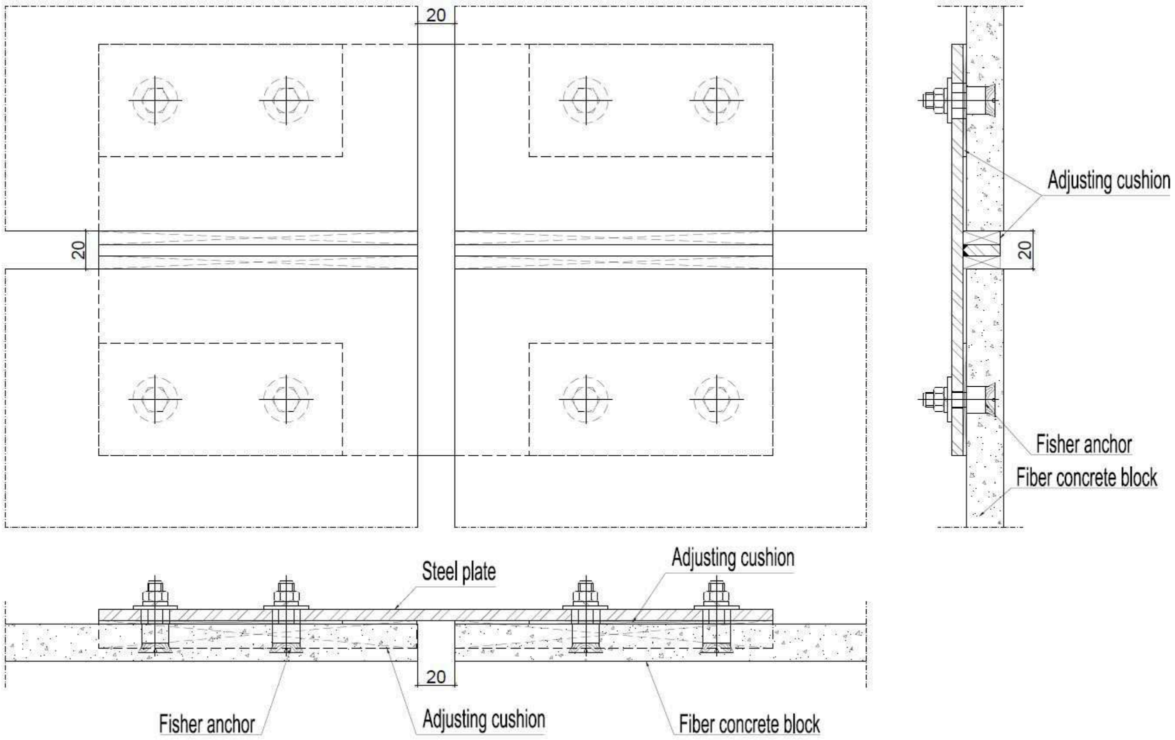

Figure 9 *A cast-in connection.*

The connection is only visible from the inside of the element, allowing the outside of the Artwork to appear as a single monolithic shape. However the connection was more labour intensive and the connection protruded into the inner space compared to the 2 other proposed connection types.
The third connection was a more complicated connection which relied on the an anchors to be fitted into the concrete plate to be able to transfer the loads between each element. The connection is shown in Figure 10.

The embedded anchors have the visual advantage that they cannot be seen from the front side. The solution is on the other hand limited to automated premixed concrete panels. The anchors have been tested to a design shear load of 1,7kN.

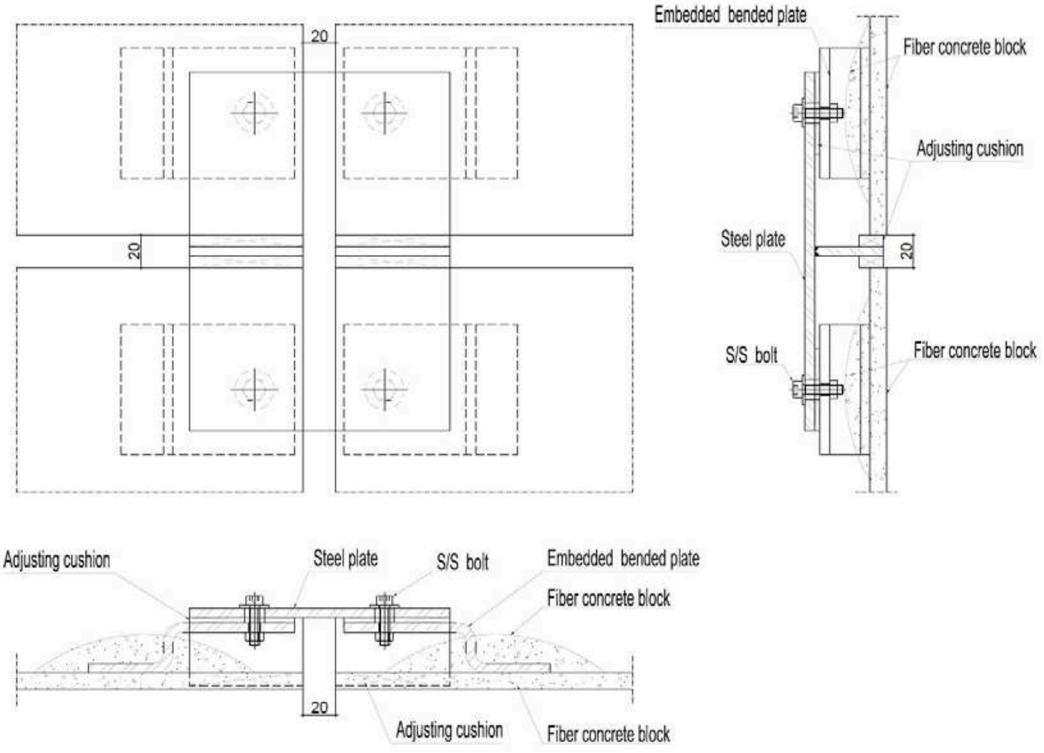

Figure 10 *An anchor bolt embedded in the concrete plate.*

MANUFACTURING OF ELEMENTS

The elements for the Artwork were intended to be manufactured using the spraying method (3) (4), because it allowed the thin-walled GFRC elements to made with an acceptable surface quality, with fewer rejections. The spraying method also allowed a connection detail to be imbedded into the GFRC element, thus allowing small moments to be transferred from one GFRC element to the other. The geometric shape of the elements was formed using a flexible table (8), that allowed the shape of each element to be generated digitally based on the parametric model. The elements cast on the flexible table are shown in Figure 11.

Figure 11 *Thin-walled elements made on a flexible table.*

CONCLUSION

In this paper an Artwork comprised of free form GFRC elements has been presented. The intention was to make a self-supporting geometry using GFRC elements based on catenary geometries developed by Antoni Gaudi and Heinz Isler. The geometry of the artwork was generated using state of the art parametric software tools. The parametric model was then transferred to an FEM modelling tool and analysed. From the analysis the maximum stresses and defections were calculated and showed that the maximum stresses in the GFRC elements were in the acceptable range. However, a connection detail needed to be developed and tested, which could transfer the forces between the element so that the artwork could appear as a single monolithic shell structure. A new moulding technology was developed to fabricate the GFRC elements, based on a flexible table, that enabled the 48 moulds to be produced in a timely and cost-effective manner. It is intended that the artwork should be built in 2016, when the research for the connection details has been concluded.

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