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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