FRC IN COMPLEX GEOMETRY FACADES

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Summary: In recent years there has been an increased interest in using Fibre reinforced concrete (FRC) in High End Architectural buildings such as the Kapsarc (King Abdullah Petroleum Studies and Research Center) in Saudi Arabia, the Heydar Aliyev Cultural Center in Azerbaijan, both by Zaha Hadid Architects, and the proposed New Qatar National Museum by Ateliers Jean Nouvel. These buildings assume the usage of panels as cladding in a complex geometry context, posing ever new challenges for the industry. In this paper we aim to analyse the recent developments in applying FRC for building facades featuring complex shapes or patterns, and discuss limitations which are currently present. In the following we discuss possibilities for producing complex shaped FRC panels (single curved, double curved, varying depth). Further we discuss the limitations of these production methods. The paper concludes with an outlook on topics which need to be investigated further to meet the current architectural trends.

1 INTRODUCTION

The use of Fibre reinforced concrete (FRC) façade elements has become an architectural trend. This is seen in the recent application of FRC as a cladding material. FRC is being exploited and applied to landmark architectural buildings throughout the world. Some of the more recent buildings which can be mentioned are the Zaha Hadid bridge for the Expo 2006 in Saragossa, the King Abdullah Petroleum Studies and Research Center and the Heydar Aliyev Cultural Center in Azerbaijan [1] which are being built at the moment, and the planned New Qatar National museum by Atelier Jean Nouvel. These buildings are shown in figure 1, figure 2 and figure 3.

One of the main drivers of using FRC is to achieve a complex geometry architectural intent, both in terms of pattern and shape. Other drivers include FRC’s possibilities of texturing and coloring opaque facades. While glass has been used before to accomplish opaque freeform facades, the production of freeform glass presents disadvantages compared to FRC with respect to tolerances and cost (for the definition of freeform refer to section 3). As an example can be mentioned the station entries of the Hungerburgbahn cable car in Innsbruck, Austria, designed by Zaha Hadid Architects, where these disadvantages caused compromises to be taken regarding the architectural intent.
Figure 1: A rendering of the Heydar Aliyev Cultural Center by Zaha Hadid Architects in Azerbaijan currently being built, whose façade is clad by flat, single curved, and double curved FRC panels.

Figure 2: A rendering of the planned New Qatar National museum by Atelier Jean Nouvel, whose façade shall be clad by double curved FRC panels.
Since the station entries for the Hungerburgbahn were completed, buildings with a similar architectural intent using freeform glass have been proposed, but have not been realized. The high cost of freeform glass sets a limitation in its usage, especially in large scale projects. Therefore FRC elements have become interesting, and are being applied on large scale projects. Cost difference for freeform facades between glass and FRC is significant. This makes FRC much more attractive, since larger volumes and, to some extent, more complex geometries can be achieved. On the other hand FRC elements also have limitations both in terms of geometry and quality, which we will discuss in this paper.

2 ARCHITECTURAL DRIVERS/REQUIREMENTS

Today FRC is predominantly used as a cladding material, and it is in this form that it will be analyzed in the following. The key architectural drivers for FRC cladding elements are the surface texture of the visual parts of the elements, the colour of the elements, avoidance of visual cracks and air bubbles (bugholes) in the visible parts of the panels.

2.1 Surface texture of FRC

The surface texture of the FRC is essential to achieving the architectural intent, and in most cases a completely smooth uncracked surface is required. At the same time the panels need to have a resistance to long term external exposure of wind, acid rain, thermal shock, etc.

The question is; how can this be achieved? The answer lies in the production method which is used to fabricate the FRC panels. A major challenge is to achieve the same surface quality on the front of the panel as well as the 4 adjacent sides, which is especially important if architectural intent requires the gaps between adjacent panels to be emphasized and the panels should have a monolithic appearance. This means that the panels have to be cast and need to have an edge return to achieve the monolithic appearance. Figure 4 shows the difference between a flat panel made using an extrusion process, where the edges have been cut to give the intended shape, and a flat panel with an edge return which has been cast in a mould. Both panels are made from a premixed concrete. The complexity of the panel can then be increased by changing the geometry of its front face from flat, to single curved (developable), to double curved. The difference between these types is described in section 3.
2.2 Colour of the panels

The topic of colour consistency of the FRC panels is important to mention, especially for large scale projects. It is difficult to produce large number of façade panels with the exact same colour. The large amount of panels requires many batches of different mix and at the same time the different panels might be curing in different environmental conditions. This would normally result in colour variations of the panels. The precise effects which govern the change in colour under curing are outside the scope of this paper. Having a big colour variation between two adjacent façade panels, makes the building look like a chessboard and is not a desired effect. The issue of colour variations needs to be discussed and quantified.

2.3 Surface cracks

The requirement of non visible cracks in FRC panels is an interesting topic, since the concrete cannot utilize its full tensile strength without engaging the fibers in the matrix. The questions which need to be asked is; which crack sizes are visually acceptable, both when the panel is dry and also in a wet condition. Normally cracks with a crack opening under 0.1 mm will not be visible to the naked eye, however if the concrete surface is wet then cracks with a smaller crack opening will become visible. Figure 5 shows an example of visible cracks formed under the curing process.
2.4 Air-bubbles (Bugholes)

The forming of air-bubbles presents the same challenges as surface cracks. Questions to be asked are: What is an acceptable diameter of a bughole and how many air-bubbles is allowed in one panel. Methods to minimize the effect have been described in detail in ACI 309 [2]. The problem is reduced in FRC panels because of the use of fine grained aggregates, but it is not avoidable. Especially when the panels are cast then this issue becomes more significant. Figure 6 shows a bughole in a flat extruded FRC panel.

For cast panels exhibiting double curvature the problem becomes bigger since the curvature of the moulds makes it more difficult to get the air-bubbles out.

![Figure 6: Bughole in a flat extruded FRC panel.](image)

3 FREEFORM ARCHITECTURE USING FRC

The usage of FRC panels in freeform architecture is becoming increasingly relevant, especially because of the FRC being applied in high end architectural buildings. As a result there are increased requirements for the production of geometrically complex FRC cladding elements. In this section we describe relevant geometric insights. A good overview of this recently evolved research field called *Architectural Geometry* can be found in [3].

Architectural freeform designs typically undergo a process called rationalization, whereby the original architectural design is transformed such that it becomes feasible (i.e. cost is lowered), while preserving the architectural intent as far as possible. Production cost is directly linked to geometric complexity, therefore rationalization techniques as described in [4] and [5] always address geometry. In the following we present a classification of curved FRC panels. This classification always applies to the front face of FRC panels only. Further complexity is added if panels have non-constant thickness, e.g. if they possess elements like edge returns.

3.1 Flat panels

Flat panels obviously always offer the possibility with least complexity for realizing freeform designs. A straightforward method for approximating freeform surfaces using flat panels is triangulation. Approximating freeform surfaces using flat quadrangles as described in [3] is more involved than triangulations, such panelisations however offer advantages over triangulations with respect to material waste, total seam length and complexity of substructure, dependent on the maximum producible raw panel size.

Geometric complexity may also be caused by irregularity of panelisation pattern, as can be seen in figure 3. In this example, a large amount of unique flat panels causes challenges for production and logistics.
3.2 Single curved panels

Single curved (also called developable) surfaces can be deformed to the plane without stretching or tearing, figure 7 shows examples. This property is very important for certain production processes like extrusion, making use of fibre mats or plastic foils which do not allow other deformations. Special types of single curved surfaces, offering additional regularity useful for production, are given by rotational cylinders or cones. Single curved surfaces are special types of ruled surfaces (they are generated by the continuous movement of a straight line in space), which allows mould production using hot wire cutting. In [4], and references listed there, techniques allowing approximation of freeform surfaces by single curved surfaces are discussed. Figure 1 shows an example of a project where a large number of single curved FRC panels is used.

![Figure 7: Single curved panels. Red lines depict straight lines. Top left: Right circular cylinder. Top right: General cylinder. Lower left: Right circular cone. Lower right: General cone.](image-url)
3.3 Double curved panels

Double curved surfaces can not be deformed to the plane without stretching or tearing. In practice this means that material which is produced flat, can not be deformed to double curved shapes. Cast panels using moulds are necessary for the production of double curved panels, adding additional complexity and significant cost. Usually there is a strong motivation to reuse (parts) of moulds for several panels. Therefore optimization algorithms have been developed, allowing to trade off reproduction quality of the original freeform surface with mould complexity and reuse [4].

Further classification of double curved surfaces yields possibilities for simplification of mould production:

Ruled surfaces

Ruled surfaces are generated by the continuous movement of a straight line in space, see figure 8. This property means that moulds can be fabricated using hot wire cutting with one cut. Every single curved surface is a ruled surface, not every ruled surface is single curved. If a ruled surface is not single curved, it always has negative Gaussian curvature, i.e. it is locally shaped like a saddle. [5] gives an extensive treatment of applications of ruled surfaces in architecture.

![Figure 8: Ruled surface panel. Red lines depict straight lines.](image)

Ruled surfaces are generated by the continuous movement of a straight line in space.

Translational and rotational surfaces

These types of surfaces carry two resp. one family of congruent curves: Translational surfaces are generated by the movement of one profile curve along another profile curve, while rotational surfaces are generated by the rotation of a profile curve around a given axis, see figure 9. This property can be exploited for mould production.
Translational surfaces carry two families of congruent curves (green and red curves on left side), while rotational surfaces carry one family of congruent curves (red curves on right side) as well as circular arcs. These properties can be exploited for mould production.

**General double curved surfaces**

All remaining double curved surface types, which do not offer any regularity.

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4 PRODUCTION POSSIBILITIES OF FREEFORM FRC

The production of FRC panels used as Façade cladding is generally divided into two different production methods, sprayed and premixed. The sprayed production method is widely used, but predominantly in the US. The production methods of sprayed panels are described in detail in [6]. However the main focus in this paper is on the production with a premixed matrix. The production of premixed panels is usually cast, however recently production-lines which can extrude flat panels for use in high end architecture have been developed. In the following we describe the possibilities and restraints of the different classifications of panels, with the focus on panels for advanced geometrically...
building as described in section 3.

4.1 Flat Panels

Flat FRC façade panel is the most common product in the industry and is being used widely, in [7] the application over the last decades is described in detail. Though for flat panels an increased complexity has developed with the realisation of complex geometry buildings i.e. the Kapsarc project. In these projects there is a large amount of unique shaped panels. If an edge return is required, as it is the case on the Kapsarc project, then each unique panel requires a similar unique mould to enable the panels to be cast.

For the cast panels where the FRC is premixed it is necessary to build moulds for each shape which is required. The cast panels typically do not have a high tensile capacity, and the panel tends to be thick to accommodate this fact. This limits the distance which the panel can span, and increases the weight of the panel, which is an issue when the panel has to be installed on site.

If there is not a requirement for an edge return then the flat panels can be produced on an extrusion line. The limitation of panels is then usually the width of the extrusion line and the length of panels that can be handled and transported without breaking. The thickness of panels is limited to 10-20 mm. On the extrusion line it is possible to use textile reinforcement. This increases the tensile strength dramatically. The strength of textile reinforced concrete (TRC) is described in [8]. The increased tensile strength has an impact in the thickness, which results in thickness between 10-20mm. The extruded panels are produced in similar ways to the float line plants for glass. Therefore the panels have to be cut into the right lengths after production. The panels can then be cut into the intended shape after it has cured. On figure 11 is shown the process of cutting panels into the final shapes. Additionally coatings can easily be applied on the surfaces of the extruded panels.

![Figure 11: Cutting a raw extruded panel into several façade panels for the KAPSARC project.](image)

4.2 Single curved panels

Single curvature panels are becoming architectural more interesting, since they can help give a
continuous context to a building envelop. As for flat panels then it is possible to use cast panels however extruded flat panels can also be used. After production, but before the panels start to harden, they are placed in shaped moulds, and remain there while they are being fully cured. Using the extruded panels assumes that the panels have the same thickness throughout the panels.

In figure 12, a mock up for the Heydar Aliyev Cultural Center is shown. The panels are produced from extruded flat panels which were placed in moulds produced by hot wire cutting.

The disadvantage of using extruded panels is that the cut sides do not have the same surface texture as the cast top surface.

Panels which are cast in their final single curved form do not have the same limitations as the extruded panels, however as described in section 2, then production quality is an issue, and it can result in many rejections which increase the production cost and time, at the same time the panels have limited tensile strength. Moulds for single curvature panels are additionally expensive.

Figure 12: Mock up for Heydar Aliyev Cultural Center, showing single and double curved panels, produced by FibreC.

4.3 Double curved panels (low curvature variation)

Double curved panels with low curvature variation, like spherical surfaces or surfaces shown in figures 7-9, are difficult to produce when using extruded planes with the current textile reinforcement. The textile reinforcement folds during the curing phase. This was also shown in [9]. This means that to produce double curvature panels it is in most cases necessary to cast the panels in a mould. The moulds for double curvature panels are usually produced by milling foams or similar into the intended geometry.

4.4 Freeform panels (high curvature variation)

The only possibility to produce pure freeform panels is by casting the panel in a mould. The moulds are usually produced with a CNC machine which can mill the correct geometry to form a surface which has the intended shape.

However new solutions with computer controlled flexible moulds, which can generate freeform shapes have been developed both at TUDelft in The Netherlands [11] and at Aalborg University in
Denmark [10]. The flexible systems are still limited in size, the maximum change of curvature and the tolerances which can be achieved. However the methods will be implemented into production lines in the new future and set new standards for what can be achieved. The disadvantage of the flexible moulds is the curing time. For FRC panels the concrete need to cure 28 days in a controlled environment to be able to control the colour variations of the panels. This makes it difficult to utilize the flexible moulds effectively.

In other industries methods have been developed where the material is printed on a computer guided automatic preshaped mould. However this would require that the textile reinforcement be developed so it is flexible enough to accommodate the changes in curvature. However panels with textile reinforcement or similar is the future because of the tensile strength.

5 CONCLUSION

In the paper the usages of freeform FRC cladding elements has been exploited. The architectural requirements which drives the acceptable standards for visual appearance of the surface texture; colour variations, elimination of visible crack, and air bubbles, have been discussed. These phenomenons's are difficult to control or completely eliminate. It is necessary to develop ways of quantifying acceptable colour ranges for the concrete, especially when large quantities needs to be manufactured. FRC extruding lines ensures more continuity in quality and to some extend limits the phenomenons. However as shown then there are limitations in dimensions and which geometries can be produced.

A geometric classification of the FRC panels has been suggested; Flat panels, single curved panels, double curved panels with low and high curvature variation. It has been discussed how these different geometries can be created, from a complex geometry architectural intent. Further we shown which computer tools can be used to modify the geometry slightly to develop geometries which can more easily be panelized.

In terms of current production possibilities then extruded FRC panels with textile reinforcement have increased the flexibilities in it usages for complex geometric high end architectural buildings. However there are still areas where production could be developed to meet the requirement of complex geometry visual architectural requirements and high tensile strength.

Further works; In relation to the architectural requirements for the surface texture, then it is necessary to do additional research to find and quantify the drivers. In terms of the future usages of FRC panels with complex geometry shapes improvements and new productions methods need to be analyzed in collaboration with the industry. Additionally is the aim to the research to investigate the usage of FRC panels as structural elements which can accommodate in and out of plane forces and at the same time be able to transfer the forces between the different panels.

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