PARAMETRIC DESIGN OF SCULPTURAL FIBRE REINFORCED CONCRETE FAÇADE COMPONENTS

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Abstract. This paper presents the first stage of a study examining the digital design and fabrication of a parametrically defined sculptural concrete façade element employing fibre reinforced concrete. On the background of a literature review of related precedent studies, the paper extends the scope of previous studies by offering a detailed insight into the process of integrating architectural considerations with material properties of fibre reinforced concrete, detailed structural analysis and construction constraints. The paper offers technical details with a focus on material to similar on-going studies.

Keywords. Parametric design; digital fabrication; digital prototyping; fibre reinforced concrete; prefabrication.

1. Introduction

Digitally driven architectural design and fabrication technologies have developed at great speed over the past decade. New kinds of architectural shapes as well as new types of production methods are becoming more common, including robotics and large-scale 3D printing technologies (Fischer and Herr 2016). Furthermore, fabric formwork has introduced new form languages, as illustrated by the experimental works by Remo Pedreschi (2012) and various others. This paper specifically focuses on sculptural concrete elements forming part of architectural façades. Architects have long been interested in sculptural concrete facades, but encountered limitations and constraints stemming mainly from limitations of concrete as material for delicate geometries and increased costs necessitated by specially made formwork. In response, architects have developed various modularization and rationalization strategies (Dritsas 2012, Fischer 2012) over the past decades that seek to find a compromise between cost-effective re-use of a limited set of formwork elements while achieving a reasonable degree of variation in the façade element design. Typical examples in architecture include the O-14 tower designed by Reiser and Umemoto, who used a limited set of standardised openings to design and construct a seemingly irregular load-bearing façade. Another contemporary example is the façade of the Broad Museum designed by Diller Scofidio and Renfro, illustrating a modularization strategy of minimizing the number of different façade panels while maximizing architectural effect. Using
similar rationalization strategies, most contemporary sculptural concrete facades employ some form of non-loadbearing prefabricated cast concrete panels, which are typically supported by a secondary façade structure (Henriksen and Schiftner 2012). A characteristic example for this design approach is the façade of the IBS Institute of Science and Innovation for Bio-Sustainability at Minho University / Portugal, designed by architect Cláudio Vilarinho (Figure 1).

![Figure 1. Precast concrete modular façade panel system ©Joao Morgado.](image)

### 2. Free-form concrete building elements in architecture

In light of current research as well as recent material advances, this study projects that a next step in the development of sculptural concrete facades will be the production of mass-customised, three-dimensionally sculptural concrete elements. Making use of advanced digital fabrication methods, existing typologies will be extended to offer architects new design opportunities. At architectural scales, advanced digital fabrication methods aiming at full-size regular building component production, such as 3D printing, are increasingly employing fibre reinforced concrete (FRC). FRC allows controlled deposition with limited addition or even the entire elimination of steel reinforcement bars (Blonder and Grobman 2015, Martins and Sousa 2014, Hack and Lauer 2014), which extends the range of possible shapes for architectural design and significantly reduces the required thickness of architectural elements.

Contemporary fabrication technologies are driven by design and research approaches that embrace entities exceeding the realm of the physical built environment - such as forces, parameters, agents or data. The designer thus works with a multi-scalar design environment in which various requirements, including physical forces which produce such as strains and stresses can be embedded as dynamic constraints within the design process (Tedeschi and Lombardi, 2017).
This change significantly affects the way in which forms are conceived, and allows a move away from classical style-driven design approaches towards data-driven, parametric shape definition. From this move, the challenge arises to coordinate parametric design approaches with materials and construction processes. Various precedent studies have illustrated an increasingly smooth interplay of parametric design and digital fabrication in the field of sculptural concrete façade design, but mostly focused on flat cast panels. A key precedent study in the context of this paper is the on-going work presented by Form Found Design (Sarafian and Culver 2017), who use variable fabric formwork to create differentiated moulds for cast concrete prefabricated elements. Façade elements thus produced are sculptural in three dimensions and uniquely shaped. Small in scale, individual elements are mounted on a load-bearing substructure in several layers and described by the designers as “self-supporting façade shading system”. Sarafian and Culver (2017) describe their use of fibre-reinforced concrete, yet also rely on internal cables for tension reinforcement of elements. Several precedents featuring three-dimensional sculptural concrete can be found beyond façade elements, such as the sculptural columns produced by XTreE (2017) using 3D printed clay for removable formwork, or 3D printed grids filled with concrete pioneered in the Mesh Mould project presented by Hack et al. (2017). Only few precedents however give a detailed discussion of the factors leading to decisions made in the mutual adaptation of material, architectural form and construction.

2.1. AIMS AND SCOPE
This paper aims to map key parameters relevant to the design of sculptural concrete facades employing FRC. To this end, it surveys the state of the art in the field and discusses initial outcomes of a study that examines the relationships between digitally designed architectural form, material properties of FRC and related construction methods. As part of a broader study, this paper focuses primarily on constraints and opportunities emerging from the interplay of architectural form and material properties. A generic design case study serves as a test bed for cross-disciplinary examination of challenges and possibilities encountered in the design process. By addressing questions of architectural form in the context of structural and material requirements, the study enables and supports constructive feasibility of future physical realisations of such structures. The paper aims to inform both the architectural design as well as the engineering approach underlying new types of digitally designed and fabricated spaces.

3. Fibre-reinforced concrete: Material opportunities and constraints
A key constraint in the digital design (and fabrication) of sculptural concrete façade elements is the necessity to include reinforcement within the naturally brittle concrete material. Since conventional steel reinforcement bars are difficult to adapt to complex sculptural shapes, most precedent studies discussed above have employed FRC. This section expands the scope of previous work with a dedicated - if brief - discussion of relevant material characteristics, already with a view to the parametrically designed case study discussed in the subsequent section.
3.1. ADDRESSING CONCRETE BRITTLENESS

To avoid excessive brittleness of concrete elements and to allow the construction of sculptural façade elements, a number of interrelated factors have to be considered:

- **Mix design**: A good workability of the concrete mix is needed so that fibres can be dispersed homogeneously during the production process.
- **Fibre content**: This relates to both workability and mechanical properties of the resulting material.
- **Shape of the architectural element**: This factor is important since it affects the orientation of fibres and the mechanical properties of the material.
- **Size of the architectural element**: The bigger the element, the easier to achieve a homogeneous reinforcement distribution within the element.
- **Size and shape of the fibre**: Increasing the size of the fibre results in more favourable mechanical properties of the concrete. Decreasing the size of the fibre however makes it easier to achieve a homogenous material, allowing for smaller element sizes.

3.2. CONSTRAINTS IMPOSED BY THE CASTING PROCESS

For the FRC casting process, the relationship of fibre size and element geometry determines feasibility of construction: If the length (size) of the fibre is bigger than the dimensions of the element (thickness), part of the elements can get clogged and the element cannot be produced. By rule of thumb, only fibres or aggregates should be employed that in their length and diameters do not exceed 2/3 of the smallest element dimension (thickness). We define an element thickness of at least 50 mm and at most 100 mm as appropriate for the selected architectural scale. For the purpose of the case study, fibre size is thus limited to 33 mm. Given this very limited fibre size, the case study may adopt a special FRC type: Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). This is mainly due to the size of the fibres. A FRC requires fibres with lengths of at least 40 mm (> 33 mm) in order to have mechanical properties superior to an (unreinforced) Portland cement concrete. UHPFRC can be produced with fibres with a length lower than 12 mm (Eide and Hisdal 2012).

3.3. MATERIAL PROPERTIES

For the purpose of this study, two main ‘families’ of FRC are presented: FRC and UHPFRC. For FRC Steel FRC (SFRC) and Polypropylene FRC (PPFRC) are considered as they represent two of the most used FRC in the market. For the UHPFRC, only steel fibre reinforced concrete (UHPFRC) is considered. Table 1 presents ranges of experimental values of compressive strength \( f_{cm} \) and tensile strength \( f_{ctm} \), which are related to the matrix, and residual tensile strength for each concrete. The last parameter is given by \( f_{R3m} \), which is related to how the fibres perform after the concrete cracks. This parameter is used in the Model Code 2010 to design FRC structures and it is related to the ductility (toughness) of the FRC being considered one of the most important characteristics of this material. The values in Table 1 show higher mechanical properties for UHPFRC, independently of the property studied. Considering this and the constraints
imposed by the casting process, UHPFRC will be considered in future stages of this study.

Table 1. Properties of concretes reinforced with fibres.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SFRC</th>
<th>PPFRC</th>
<th>UHPFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{cm}$ (MPa)</td>
<td>30-40</td>
<td>30-40</td>
<td>150-200</td>
</tr>
<tr>
<td>$f_{cm}$ (MPa)</td>
<td>3-4</td>
<td>3-4</td>
<td>15-20</td>
</tr>
<tr>
<td>$f_{k3m}$ (MPa)</td>
<td>1.50 (15 kg/m$^3$)</td>
<td>0.75 (2.5 kg/m$^3$)</td>
<td>10.00 (0.5 kg/m$^3$)</td>
</tr>
<tr>
<td>$f_{k3m}$ (MPa)</td>
<td>3.00 (30 kg/m$^3$)</td>
<td>1.00 (4.0 kg/m$^3$)</td>
<td></td>
</tr>
<tr>
<td>$f_{k3m}$ (MPa)</td>
<td>5.00 (45 kg/m$^3$)</td>
<td>2.50 (6.0 kg/m$^3$)</td>
<td></td>
</tr>
</tbody>
</table>

Regarding the type of fibres utilized in the production of UHPFRC, the authors consider twisted fibres (e.g. hooked fibres, Figure 2 left) and coated straight fibres (e.g. copper-coated straight fibres, Figure 2 right). Considering these two types of fibres, the affection of physical and chemical fibre-matrix interface friction will be integrated in the analysis in the following steps of the study (Naaman 2003).

![Figure 2. Fibres for UHPFRC: hooked (left) and copper-coated straight (right).](image)

3.4. FORMWORK

Sculptural forms constructed based on concrete typically require formwork, with the exceptions of sprayed concrete, such as presented by Hack and Lauer (2014) as well as Hack et al. (2017). In both cases, construction processes present key challenges and constraints. This study focuses on construction techniques of casting and 3D printing, both of which are capable of producing surfaces suitable for the production of architectural façade elements. For the purpose of this study, we assume a cast FRC façade element using 3D printed formwork to achieve the intended architectural results, aiming for both a reduction of material permitted by employing FRC as well as a potential reduction of formwork to save cost, time and CO2 emissions. The question of formwork will be examined in detail in the following stage of the study, with this paper introducing primarily the mutual influence of architectural form, material properties and structural performance.
4. Design case study: Freeform concrete façade element

To investigate the interrelations between architectural geometry, material and construction, we examine a prototypical lattice structure composed of self-supporting sculptural façade elements. Each element is assumed to support only itself, with gravity as well as wind load equal to 2500 kN/m² (top of a 15 story building in the South of United Kingdom) applied axially and laterally, respectively. Façade elements are attached to a load-bearing steel frame connected to the main building structure. The size of each façade element is limited to one square metre (a square of 1m x 1m) with a thickness between 50-100 mm to allow for a variety of fabrication strategies as well as physical load testing at a later stage of the study.

Figure 3. Early parametric variations of wool thread-inspired façade element geometries.

The parametrically defined geometry of the façade modules (Figure 3) is inspired by physical experiments pursued at the Institute for Lightweight Structures (Otto 1992) and modelled in Rhinoceros3D and Grasshopper. Geometry was initially generated on the basis of lines in analogy to the physical process of optimizing vertical load paths by letting loose wet threads develop localized clusters, while both top and bottom ends of the structure remained fixed. This approach allows the façade element geometry to accommodate vertical load paths as well as fixed top and bottom edge conditions, while at the same time generating variety within the element shapes. Considering material thickness and size of the façade element, we defined the geometry at eleven threads and a random assignment of top and bottom ends of the threads. When developing the parametric model, we switched from a thread-based to a surface-based model to allow for three-dimensional model building with varying thread diameters.

Figure 4. Structural analysis of parametric geometry with material properties.

During the prototyping stage of the study, the initial parametric model
was iteratively adapted to accommodate the structural capabilities of FRC. We considered length of fibres in relation to the façade element thickness as well as a geometrical response to structural requirements in terms of applied loads and resulting stresses. Figure 4 illustrates the process of developing the parametric geometry through structural analysis feedback. A separate software (Finite Element Method (FEM) analysis software Oasys GSA Suite) was used for structural analysis at this stage to inform geometry development in Rhino/Grasshopper. At first, the vertical threads were conceived as straight segments of varying lengths (Figure 4 left) as well as varying diameters (Figure 4 second from right) and analysed for structural performance under gravity loads (Figure 4 second from left, far right) as well as wind loads. The analysis indicated that the façade element performs well in both load cases when assuming the material to be UHPFRC, with maximum Von Mises stresses of less than 125 MPa, well within the compressive strength range of UHPFRC (See Table 1).

The structural analysis further indicated that stiffness of the façade element can best be improved by adapting the geometry by adding thickness to the cross sections at or close to the intersections of threads as well as near the supportive external frame. The next stage of design development thus resulted in a sculptural element consisting of smoothed three-dimensional meshes with added thickness in the intersections of the vertical threads. Figure 5 presents the process of parametric geometry variation, generated from eleven intersecting straight lines, relaxed and clustered simulating wet threads, and subsequently converted to smoothed sculptural meshes. The drawings in Figure 5 illustrate (from left to right): initial NURBS line geometry, raw meshes, two stages of relaxed meshes as well as initial results for displacements and von Mises stresses (results for the latter obtained from Grasshopper plug-in Millipede).
Figure 6. Structural analysis of final façade element geometry.

Figure 6 illustrates results obtained from the structural analysis (using FEM analysis software Oasys GSA Suite) of the final façade element geometry: On the left, the Von Mises Stresses resulting from gravity and wind load, resulting deformations (middle) and Von Mises Stresses resulting from gravity loads only (right). For the structural analysis the geometry was approximated through shell elements of 100 mm thickness. Results from the Oasys GSA Suite analysis, considering gravity load, were found to match and confirm structural analysis results obtained from the Grasshopper plugin Millipede, which will allow for integrated structural performance assessment as part of the parametric form generation in the next step of the study. The suitability of FRC was confirmed in the initial structural analysis.

5. Discussion: Impact of material constraints on architectural design

The preceding sections offer a detailed look into the development of a sculptural façade element employing UHPFRC. While previous studies have primarily focused on aspects of geometry and fabrication, this study examines the integration of architectural geometry with material, structural and construction considerations. We find that although FRC offers great opportunities for sculptural façade design, required fibre lengths of regular FRC and the small diameters of the façade element geometry limit the available material choice to UHPFRC in the case of this study. With UHPFRC offering sufficient toughness, the use of glass fibre and basalt fibre as suggested by Sarafian and Culver (2017) offers little improvement for material brittleness and is found unnecessary in the case of this study (Eide and Hisdal 2012, Branston et al. 2016), and steel fibers will be considered in the subsequent stages of this study. The parametric form language developed for this study is oriented towards continuity of vertical load paths and resists horizontal loads through stiffness generated by enlarged sections at intersections of threads and connections to a supporting exterior frame. Structural analysis results informed parametrically defined geometries, resulting in relatively even stress distribution throughout the façade elements. The form language furthermore
supports casting of the sculptural forms in UHPFRC from the ends of the threads. Beyond the immediate requirement to generate structurally viable elements, the study also generates other questions relating to the notion of optimisation to be followed up in the next stages of the study. In the age of mass-customised architectural elements that fulfil aesthetic as well as structural and economical requirements, optimisation is not straightforward and needs to be differentiated from conventional engineering-based notions of optimisation (Paoletti and Naboni 2014, Holzer et al. 2007).

6. Summary and outlook

This paper presents initial findings of a larger study addressing the integration of architectural design intentions and the material and construction requirements of fibre reinforced concrete in a self-supporting sculptural façade element. A generic parametrically defined façade element is analysed and discussed. Initial findings indicate that in the case of parametrically designed sculptural façade elements of a size of 1mx1m and a thickness between 30 and 100mm, material strength of the chosen UHPFRC is less relevant for architectural form development than construction requirements relating to the sculptural shape of the façade elements and the length of the fibres employed. Furthermore, axial and shear stresses within the façade elements due to gravity as well as wind loads cause only limited deflection and can be addressed by forms providing sufficient stiffness. The chosen wool thread inspired form language was found successful in generating sculptural shapes that deal well with applied gravity and wind loads, but had to be transformed into a surface-based model to become usable for design and analysis purposes. For the next step of the study, questions of formwork and construction emerge as main critical questions for investigation. With the next step, we intend to examine whether hybrid reinforcement strategies integrating steel cables are realistic to support the façade element geometry and to reduce required fibre content as well as embodied CO2. We also aim to address the fabrication of the three-dimensional sculptural shapes by employing UHPFRC in combination with 3D printed formwork, which also promises suitable interfaces for connections to load-bearing support structures.

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