Simplifying Doubly Curved Concrete

Post-Digital Expansion of Concrete’s Construction Solution Space

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Abstract. This action research project develops a novel conceptual method for non-standardised concrete construction component fabrication and tests its validity through a speculative design project. The paper questions the practical, procedural and economic drivers behind the design and construction of geometrically complex concrete architecture. It proposes an alternative, simple and economical fabrication method for doubly curved concrete centred on the robotic manufacturing of casting moulds through 5-axis hotwire foam cutting for the making of doubly curved fiber-reinforced concrete (FRC) panels. These panels are used as light-weight sacrificial formwork for in-situ concrete casting. The methodology’s opportunity space is tested, evaluated and discussed through a conceptual architectural design project proposal that operates as demonstrator. The paper concludes by addressing the advantages of a design-and-build architecture delivery setup, the potential from using computational technology to adapt conventional design and construction procedures and the expanded role within the design and construction process this gives to architects.

1. Introduction

With recent advancement in robotic and digital fabrication technologies, computer-driven production tools have become more widely accessible, even in developing parts of the world. This enables architects to participate in the development of methods and tools that allow greater integration of construction processes in the architectural design.

This paper discusses an action research project that develops a novel conceptual method for non-standardised concrete construction component fabrication based on a bespoke piece of computer-controlled manufacturing equipment and tests its validity through a speculative design project. The study’s objective is to expand the design solution space of a developing construction context through direct numeric control over specific aspects of the production
process while remaining within a cost-effective operational model. Rather than viewing mould-making solely as a component from the construction process that is consecutive and supplementary to the initial architectural design process, the study hypothesises that direct control over the mould-making process can positively link the design and construction solution space for concrete architecture, thus increase the design agency of an architect-led design-and-build team.

In doing so, the paper challenges conventional procedures of architecture design and construction. With information and simulation tools available on specific construction methods and associated implementation costs, architects can directly affect the work-flow of a construction project and, in return, integrate practical constraints as early-stage design drivers of the outcome.

2. Concrete in the “Post-Digital” architectural era

Modern methods of mass production originate in the industrialisation period. From the mid-19th century onward, assembly lines rapidly increased the speed of production of standardised goods, dramatically effecting both traditional craftsmanship and architecture. While, originally, buildings were primarily designed and built in direct response to local conditions, such as available materials, construction methods, building traditions and craftsmanship, the standardisation of construction elements ‘discretised’ this fluid design solution space into a series of economically favourable outputs defined by standardised parts.

Today, computer-aided design and manufacture have the potential to undo this process. According to William J. Mitchell (2004), “Today, innovative applications of computer-aided design and manufacturing technology are allowing architects to transcend long-standing limits on complexity and, thus, to respond more sensitively and effectively to varied human needs and construction contexts”. Yet, little of this potential can be felt in everyday building production. The construction industry seems remarkably recalcitrant to this evolution and largely remains the low-tech, high-touch enterprise it has been for decades.

While the conceptual disruptions from digital technologies have already largely occurred in academic lab environment, change in practice will not take place through such technologies alone. Applications and use opportunities of digital technologies are far from exhausted. By further translating and integrating the ever-expanding digital toolbox into practice, opportunities exist for available digital means to engage in an alternative conversation with mundane project construction contexts far from these academic labs.

Within this framework, the goal of this paper is to functionally re-purpose available digital means for mould making in the context of contemporary architectural practice. Hence, the work positions itself in a ‘Post-Digital’ context, as it addresses the humanisation of digital technologies which are brought back into the physical world of praxis, with ideas and materials informed by decades of working with computers (Crolla, 2018).

According to Adrian Forty (2016), “Concrete is modern [...]. It is one of the agents through which our experience of modernity is mediated”. 20th Century
architectural styles, like modernism or brutalism, have evolved alongside the
development of concrete construction technology: architectural ideas and building
technology mutually affected one another. This study investigates how today’s
Post-Digital context allows further diversification of the flexibility and freedom
concrete brings to architects and their spatial explorations.

3. Design-and-build

The architectural industry is typically separated into different sectors and
specialties, with clear hierarchies during different stages of a building project. This
separation of liability, responsibility and knowledge restricts the design solution
space as information is prohibited from freely flowing up- or downstream.

According to Kieran and Timberlake (2004), “[the] Master Builder [can be
defined] as a person who combined the roles of architects, builder, engineer and
material scientist.” Each of these roles plays a crucial part in the architectural
project and is interlinked with one another. But in reality, they claim, “The single
most devastating consequence of modernism has been the acceptance of a process
that segregates designers from makers: the architects has been separated from the
contractor and the material scientist has been isolated from the product engineer”.

Today, architects can directly access and control fabrication tools since
computer numerical control (CNC) fabrication tools have become a commonly
available part of the building construction industry. By revisiting these
machineries and their integration into a holistic design-and-build workflow,
opportunities can be opened for architects to incorporate their requirements into the
architectural design and effectively and directly expand the practically available
design and construction solution space.

4. Fabrication Equipment as Origin

This study started with the acquisition of a locally custom-built 5-axis hotwire
foam cutter and the ambition to integrated it in the design and construction process
of architecture that centres on the use of geometrically complex, doubly curved
concrete elements (see Figure 1). The bespoke machinery used for the study
consists of a hotwire cutter that is controlled via five separately running motors:
Two on each side of the wire define the horizontal and vertical sliding axis, and
one at the bottom of the machine drives a rotating base plate. The maximum travel
distance of the sliding axis is 1800mm, and the rotation plate can rotate 360 degrees.
The maximum vertical cutting angle between the hotwire and the foam block is 40
degrees.

Since no proprietary control software was available, a bespoke digital
simulation and data extraction setup was developed in McNeel’s 3D modelling
software Rhinoceros and its procedural modeller Grasshopper. The machine’s
straight wire setup restricts the solution space to compositions of ruled surfaces.
Per definition, a ruled surface can have a straight line placed onto the surface in
every point of that surface. The continuous path through these straight lines
becomes the path for the cutting wire. A bespoke algorithm was set up that
translates designed 3D geometry into such a series of cutting motions and translates
them into G-code that can directly be fed into the robotic setup.

Figure 1. 5-axis Hotwire Cutter.

To gain knowledge on the machine’s operational parameters, several cutting tests were carried out with different combinations of feed rate and hotwire temperature, with the feed rate ranging from 50 to 400 units/minutes, and the Voltage from 0.5V to 2V. Test results indicated that the quality of the surface finish is affected by a combination of factors, including the feed rate (cutting speed), the temperature of the wire and the cutting geometry. Simple cutting surfaces prefer higher temperatures and feed rates, while more complex surface with more turning curvature would require lower feed rates and temperatures to minimise the cut loss due to over-melting of the foam block.

5. Doubly-Curved Concrete cast Precedents

Even with today’s means for digital fabrication, the construction of moulds for doubly-concrete casting is often not economically viable or locally available. Doubly-curved concrete does not allow for conventional shuttering for in-situ casting and usually needs formwork to be tailor-made. Whereas straight timber planks can be used to produce formwork for single-curved surfaces, custom CNC-milled foam moulds are typically required for every single area with double curvature. Their reusability depends on the repetition of the areas of double curvature and is generally low for a free-form design.

This brought our research to investigate if the close integration of the opportunities and restrictions of a specific low-cost mould can be an integral part of a geometrically complex architectural design project from the early conceptual design stages onward. This project proposes an alternative approach that combines
in-situ casting with a re-usable ruled surfaced foam mould to produce doubly curved sacrificial formwork fibre-reinforced cement (FRC) panels, meaning that the formwork bonds to the concrete construction and is embedded into it.

In doing so, the project references and expands upon concepts found for example in the International Museum if the Baroque by Toyo Ito (Puebla, Mexico. 2016) (see Figure 2). The museum’s external walls are composed of precast white concrete panels and slabs that define the overall geometry of the architecture. Each precast panel consists of two panels of 64mm white concrete, joined as a sandwich panel. Those later become the sacrificial formwork for in-situ cast concrete, which is poured into the slot of the precast components. Together with the reinforcement, this locks the panels in place to form the external façade with a high degree of quality control and in a cost-effective manner. Here, however, the panels are either planar or conical in shape, heavily restricting the design solution space within which the architects could operate. We propose to expand these with doubly-curved geometry.


6. Tectonic System

Pre-casting concrete panels gives high quality control and lowers the construction cost. However, using non-repetitive single-use moulds quickly increases the construction complexity and cost of the project again. Hence, we propose to start the design from a standardised, large, reusable mould which can be produced at low-cost and high speed with a hot-wire foam cutter and is typified by a range of geometric internal variability.

As a reference, the free-form entrance to the Gare St.Lazare Metro similarly used standardised geometries to minimize the number of moulds needed for
free-form panel production, but in its case, to produce doubly-curved glass panels. All panels are derived from a spherical and toroidal, therefore only a few oversize moulds are needed. (Baldassini 2008)

A revolved hyperboloid is introduced as the base geometry for the mould. Hyperboloids are a sub-group of ruled surfaces. A hyperboloid can be defined by revolving a hyperbole. This curve is described by a simple formula with two variables \( y = a \times x^2 + b \), with \( a \) and \( b \) controlling the tightness of the radius and the size of the overall geometry.

The choice for a hyperboloid stems from its great geometric internal variation: a wide range of double-curved surfaces with different radii can be extracted from the same hyperboloid. For instance, at the centre of the hyperboloid areas with a much tighter radius are found as opposed to the more planar regions towards the outer edges. In addition, a mould in the shape of a circular hyperboloid is suitable for mass production as it can be composed of repetitive modules that are each easily individually hot-wire cut. Because the geometry is symmetrical along both vertical and horizontal axis, not the entire mould, but a smaller section can be produced to cover mass production of panel segments.

We proposal to isolate specific sub-surface geometries from a single hyperboloid mould to produce thin FRC panels. These panels can then be used as sacrificial formwork on site, with infill concrete being poured in the cavity in between two panels. Thus, the hyperboloid contains a “matrix” of possible panel geometries with varying properties. During the digital modelling stage, specific sub-surfaces are extracted to build up the project in response to other design factors, such as program, site context, design objective, etc.

The first step in the design process, therefore, is the specification of the parameters of the foam mould to allow for its production. The mould must be divided into smaller segments in response to the size limitations of available foam blocks and of the hotwire cutter. This action is incorporated in the computer script, giving the design team control of the mould production cost and time. Only then does the panelisation of the concrete wall according to the available mould geometry take place.

Figure 3 below explains the tectonic system through the construction sequences: 1) Individual mould segments are cut by the 5-axis hotwire cutter. Customised script is used to produces the G-Code for automatic cutting process. 2) The hyperboloid foam mould is assembled and coated for repeated use. 3) Required sub-surfaces are marked out on the foam mould. 4) FRC panels are cast onto the foam mould and tagged for on-site assembly. 5) Scaffolding is set up and FRC panels are assembled according to the design. 6) Where needed, additional formwork, e.g. for customised internal spaces inside the wall cavity, can be placed in-between the precast panel walls. Finally, concrete is cast on site in-between the precast panels which are used as sacrificial formwork.
7. Design application and evaluation of the tectonic system

As a next step, the proposed tectonic system is tested and refined through the conceptual architectural design development of a project that capitalises on the envisioned workflow. As a design challenge, the redesign of an existing outdoor mini-theatre in Hong Kong’s Tamar Park is chosen, with as design brief to convert it into an enclosed performance pavilion with the capacity of around 200 seats, including provision of all related functional spaces (see Figure 4).

The first step is to identify design-driven factors that allow for the mould parameters to be specified. In this design, the roof surface of the theatre space is used as a primary driver for this, as visible in the long section’s interior concave
profile of the roof of the performance space (see Figure 5). Several iterations are used to arrive at a parameter setup that allows a workable response to the design site and program.

Figure 4. Tamar Park Theatre, conceptual architectural design proposal.

Figure 5. Long Secion.

Once the mould parameters are defined, the other parts of the design are specified. A personal design objective is for the building to maximally express the spatial opportunities of the doubly-curved surfaces. Walls are therefore chosen to have a wide range of properties in terms of spatial definition and function. Different combinations of surfaces provide different space types; for instance, the combination of two differently curved surfaces (see Figure 6; see surface A and B in Figure 7) defines the entrance area which also allows natural light to penetrate the building. As the design develops, mould parameters are tweaked and fine-tuned until an equilibrium is reached.

The final building design proposal consists of five sets of doubly-curved concrete walls, each of them extracted from the same single circular hyperboloid. Figure 7 illustrates how each of these panels nests onto the mould surface and how there is no need to produce the full hyperboloid to allow for the prefabrication of each panel.
Figure 6. Lobby Entrance.

Based on practical implementation factors like intended size of individual precast panels and lead time, the design team can design the size of the actual foam mould which best fits the construction scope. Reducing the size of sub-panels of each wall segment allows, for example, for a reduction of the size of the mould segment which is subsequently more frequently reused, but this results in slower production time. For example, if we use half of the hyperboloid as the actual mould to speed up the casting, its size would become an unpractical 50m (W) x 22.6m (H) x 52m (L). A quarter smaller mould might be more cost-effective overall and measure 18.6m (W) x 22.6m (H) x 32.2m (L).

8. Discussion

This action research project illustrates on a conceptual level how an overhaul of the typical separation of the architectural industry into separate sectors and specialities could practically expand the design and construction solution space
for geometrically complex architecture. By approaching architecture production as a design-and-build challenge, productive information from implementation can feed back into the conceptual stages of the architectural design.

The strength of the specific proposed system lies in its ability to enable varied doubly-curved concrete architecture to be produced from a standardised and reusable mould. This should substantially lower the construction cost by reducing the prefabrication and on-site labour cost to produce otherwise needed complex formwork. In return, the building design remains constrained by the geometries enabled by the specified hyperboloid, making the design response to program or site a delicate balancing act.

Further study, ideally through a real-world construction project and in close collaboration with a contractor or manufacturer, is needed to test how the system functions in combination with other building systems and elements and to allow quantification of assumed parameters and related cost savings. The opportunity exists for this tectonic system to be refined and integrated in an entrepreneurial design-and-build business model.

9. Conclusion

This paper argues, through example, that in today’s Post-Digital era the practically available design and construction solution space for buildings can be expanded when architects adopt a design-and-build mentality. Because of available computational design tools and digital fabrication technology, the role of the architect can be redefined, extending scope and reach beyond the design stage and into world of project delivery. Incorporating the setup and management of construction production systems extends design opportunities within a cost-effective economic model.

The example of rethinking the role a 5-axis hot-wire foam cutter can play in a design and construction project illustrates how applications and use opportunities of available computer-aided design and manufacturing techniques are far from exhausted. And can lead to the production of architecture that can respond more sensitively and effectively to variations in human needs and construction contexts.

References