Calculated Matter

Algorithmic Form-Finding and Robotic Mold-Making

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The paper addresses a specific method for the production of custom-made, differentiated moulds for the realization of a complex, doubly-curved wall element during an international three-week architectural programme, Architectural Association (AA) Summer DLAB. The research objectives focus on linking geometry, structure, and robotic fabrication within the material agency of concrete. Computational workflow comprises the integration of structural analysis tools and real-time form-finding methods in order to inform global geometry and structural performance simultaneously. The ability to exchange information between various simulation, modelling, analysis, and fabrication software in a seamless fashion is one of the key areas where the creation of complex form meets with the simplicity of exchanging information throughout various platforms. The paper links the notions of complexity and simplicity throughout the design and fabrication processes. The aim to create a complex geometrical configuration within the simplicity of a single material system, concrete, presents itself as an opportunity for further discussion and development.

Keywords: robotic fabrication, custom form-work, generative design, structural analysis, concrete

INTRODUCTION

The digital era in architecture has witnessed the production of a vast array of geometrical assemblies through computational form-finding methods in previous decades. With the developments in digital fabrication, the production and assembly of complex forms has been compromised by the constraints of selected fabrication techniques. In recent years, robotic fabrication processes implemented in architecture have begun to incorporate digital and physical paradigms in an unparalleled way due to the multi-axis freedom of an industrial robot arm, its speed, precision, and low tolerances (Menges 2013). This development in turn has fuelled the revival of complexity found in volumetric assemblies, moving away from previous standardized / sheet-material component fabrication (McGee et al. 2013). The capacity to design and produce volumetric building components through robotic carving strategies presents itself as a novel approach where custom-made moulds can be produced with speed and precision, allowing for the creation of complex forms.
which would not have been possible with standard-
ized building materials and processes (Brell-Cokcan
and Braumann 2010).

This paper presents a specific method for the
production of custom-made, differentiated moulds
for the realization of a complex, doubly-curved wall
element during an international three-week archi-
tectural programme, Architectural Association (AA)
Summer DLAB, which took place during 27 July - 14
August 2015 in AA’s London home and Hooke Park
premises. The method engages an industrial robotic
arm mounted with a milling head, the mould material
is medium-density EPS foam, and the final assembly
is produced with fast-setting concrete. The research
objectives focus on linking geometry, structure, and
robotic fabrication within the material agency of con-
crete. In this respect, it aims to link the notions of
complexity and simplicity throughout the design and
fabrication processes. While complexity is generated
throughout computational form-finding techniques,
simplicity lies in how architectural information re-
lying to geometry, analysis, and fabrication can be
seamlessly transferred between various simulation,
modelling, analysis, and fabrication platforms. More-
ever, the aim to create a complex geometrical con-
figuration within the simplicity of a single material
system, concrete, presents itself as an opportunity for
further discussion and development.

COMPUTATIONAL WORKFLOW

A research methodology has been structured around
a set of experiments in line with the research objec-
tives. The design brief is to propose, fabricate, and
assemble a one-to-one scale architectural wall ele-
ment from concrete in a forest located in the south
of United Kingdom within a limited time frame, three
weeks. The employment of complex formwork for
concrete structures has the potential to yield mor-
phologically interesting and materially efficient as-
semblies. In the initial stages of design development,
real-time generative form-finding methods have set
the correlations between the computational process
of design with the physical world of fabrication and
materiality. Recent developments in robotic fabrica-
tion techniques offer designers with the capacity to
fabricate complex geometrical configurations thanks
to their multi-axis freedom. As such, the major ob-
jective of this case study has been directed towards
the coupling of doubly-curved complex geometrical
assemblies informed by structural analysis and their
realization through robotic milling processes.

Initial form-finding experiments have focused on
the manipulation of a vertical planar geometry to-
wards the creation of varying degrees of curvature
through a range of computational techniques. Key
parameters in this phase have comprised the dis-
tribution of openings and areas of local differenti-
ated curvature values that stem from a global mor-
phology. After preliminary tests conducted in differ-
ent algorithmic platforms, the open-source program-
ming environment Processing (Shiffman 2012) has
been chosen for further exploration for its resilience
and accessibility to create custom-made tools. In
this setup, an agent-based model approach has been
adopted. These computational algorithms simulate
the local interactions of agents in order to evaluate
complex behavioural patterns, which can then be
further developed to manipulate geometrical vari-
ation according to a set of predefined criteria. In
the early tests of the custom tool, an agent-based
system has manipulated a vertical planar geometry
constructed as a mesh, imported from the three-
dimensional modelling software McNeel Rhinoceros.
These digital experiments have been valuable in set-
ing up constraints for the agent system in relation
to the Z-axis coordinate of the agent, the distance
between the agent and the planar mesh, and the
amount of displacement the mesh face can achieve
in relation to its normal vector.

The goal of the second set of computational ex-
periments has been the integration of structural anal-
ysis tools from the outset of design explorations in or-
der to inform global geometry and its structural per-
formance. In this regard, the planar mesh in the pre-
vious experiments has been replaced with a global
grouped which

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top and an "S-curve" section at its bottom, modelled in McNeel Rhinoceros, in order to assist in structural performance. This geometry has then been evaluated under its self-weight via FEA analyses with the Grasshopper add-on Karamba as a shell structure [1]. For the analyses, material properties of high-strength concrete (C90/105) have been selected. After various tests with shell depth, a value of 5 cm. has been selected in regard to keeping displacement values at an optimal level. The output mesh model of Karamba has then been connected to the 'ForceFlow' component, a native component of Karamba, which enables the visualization of force flow lines in a shell in the global direction provided. The generation of the force flow lines has been design-oriented, with the aim of achieving wall openings which do not interfere with the transfer of loads throughout the global geometry. As such, the FEA stage has been concluded with the creation of a 5 cm. deep shell split by openings following the direction of force flow within the wall (Figure 1).

The next stage in the computational design process entails the generation of doubly-curved geometries following the initial shell model as an input. The purpose of this investigation is two-fold, pertaining to structural performance and exploration of robotic milling techniques. The tool in Processing is developed further as a combination of agent-based simulation and mesh relaxation techniques with the purpose of creating a doubly-curved geometrical aggregation that increases in density towards the bottom section of the wall. After the generation of openings, the mesh with its corresponding force flow lines has been imported in Processing for complex curvature generation. The agent system influences local mesh curvature throughout the overall form along the force flow lines following flocking and proximity rules. The magnitudes of vectors manipulating the form increase as the agents flock towards the ground plane resulting in greater mesh deformation in the bottom areas. As a result, the final mesh geometry is characterized by more local curvature and material accumulation in the bottom areas compared to its relatively straight and thin cross-section at the top. The differentiation in thickness has been a focus for the corresponding physical experiments in order to examine the variation of cross-sectional depth in conjunction with the proposed fabrication process. With the resulting tapering effect, the final outcome of the simulation has more structural load-bearing capacity (Figure 2).

**ROBOTIC MILLING AND ASSEMBLY PROCESS**

As it has been described above, the second goal of the simulation process has been to test robotic milling processes with the purpose of experimenting with complex curvatures for form-work building. In this respect, the choice of form-work material and robotic milling time have served as major inputs for the fine-tuning of applied forces in the Processing simulation. Computational experiments have been simultaneously coupled with scaled fabrication experiments before the final design output. The robotic fabrication processes in the design allow for moving away from a direct design-to-production approach, whereby the final outcome is predefined and fabri-

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**Figure 1**

FEA conducted on preliminary design in Karamba add-on for Grasshopper, followed by the extraction of force flow lines and the generation of openings on the wall.
cation solely offers a "means to an end". The tooling path serves as a direct visual connection between the global geometry and local surface manipulation; therefore, the robotic end effector plays a crucial role as a design tool in the generation of localized surface textures on the global configuration. Several path milling tools have been tested on scaled physical experiments regarding linear vs. elliptic paths, radius of tool and fabrication time. Due to the time limitation pertaining to the fabrication and assembly of the final prototype, a linear tool path has been chosen to create local surface textures with a robotic milling tool defined by a ball nose of 25 mm. diameter and 250 mm. length.

The material for the form-work has been selected as medium density (30g/l) fire retardant grade expanded polystyrene (EPS) blocks, as EPS offers a suitable compromise between milling time and strength for form-work construction. Several iterations investigating the increase of surface area in relation to milling time have been generated in Processing. The final output model demonstrated in Figure 2 is the result of this iterative process, providing a conclusion that the total amount of milling time would approximately be 30 hours.

The next stage of design development has involved the creation of the necessary form-work files for robotic simulation followed by the milling process. The output mesh generated in Processing is exported as a text file into McNeel Rhinoceros, becoming the negative geometry for the preparation of form-work. In Rhinoceros, each form-work is created by taking into consideration material dimensions and tolerances. The dimension of each EPS block is 200 cm in length, 125 cm in height, and 50 cm in depth, resulting with the employment of a total of 8 EPS blocks. As the fabrication and assembly processes need to have high precision for desired outcomes, the placement of steel bars connecting the form-work elements on two sides has been calculated in Rhinoceros as well. The location of the steel bars follows the distribution of the openings of the final wall structure (Figure 3).

The end-effector for the robot serves as a design means that aids in the generation of surface textures in the EPS boards. After the completion of the milling process that lasted 30 hours in total, the areas of contact between the scaffolding and concrete have been treated with a mixture of silicone and mold releasing agent in order to assist with the de-molding process (Figure 4). Accordingly, the EPS foam boards have been connected and secured with steel bars and plywood panels to enhance their stability. It is important to note that the structure is made of a special...
Figure 3
The creation of form-work files for robotic milling.

Concrete mix with fiberglass additives which has enabled it to be cast, dried and held strongly in place in a period of several hours without being limited by the constraints of applying conventional reinforcing systems such as rebar. The only location where rebar has been used in the final fabrication has been along the foundation of the wall, bearing a depth of 30 cm.

Figure 4
A section of EPS form-work after it has been treated with silicone and release agent.

Concrete has been selected as the most suitable material for casting. The final concrete mixture is fast-setting with fiberglass additives thus excluding conventional reinforcing systems such as rebar throughout the wall element, except along the bottom parts where it is linked to its foundation. The final assembly stages have involved the casting of fast-setting concrete in the EPS form-work, followed by the curing time of approximately 12 hours. With dimensions of 2.2 meters height, 4 meters width, and a varying depth of 30 - 250 mm, the final wall assembly has been developed, fabricated, and assembled in 7 days (Figure 5).

CONCLUSIONS
While this research has been applied for the realization of a wall in the context of the international programme, it has future potentials applied on more complex architectural elements. One of the limitations during the fabrication stage has pertained to the time constraints to produce the moulds; therefore, the tooling path had to be comprised in order to maintain realistic production times. The modularity of the form-work was a challenge for the concrete pouring of the entire structure as the final placement of the form-work pieces caused a thinner space in-between due to the milling pathways used. However, due to the precision of the robotic milling the surface continuity was achieved via specific markings on the blocks. Due to the increased temperature of the fast-setting concrete, the EPS blocks were fused with the thin partition rendering of the latex coating, making it highly challenging for the demoulding. Together with the double-curved profile of the wall as well as

Figure 5
Final wall structure, overall perspective.

As the final structure would be placed outdoors, it has been crucial that it resists the cold and humid weather conditions of its environment; therefore,
the undercuts, the removal of the EPS blocks required a delicate but powerful approach. An ideal formwork setup would comprise EPS blocks with thicker coating, larger openings on the wall surface, and wider profiles at the lower parts of the partition in order to ensure the consistency in the concrete pouring. The computational simulations on structural analysis that showed the distribution of forces proved to be true in terms of the even distribution of displacements along the height. As the final prototype resulted in being critically thinner than initially computed, the fact that it can hold its own weight acts as a proof of the successful implementation of physics behaviour, the material properties of concrete (Figure 6).

The integration of robotic techniques is advantageous due to the capacity to explore volumetric spatial formations as well as to incorporate real-time feedback for future explorations. The design and fabrication processes have demonstrated the strong independence between the digital and physical paradigms. The computational simulations have taken real-world constraints into account with the integration of structural analysis. Digital simulation on structural analysis proved to be accurate compared to the final outcome. Throughout the design, fabrication, and assembly processes, the interactive associations between different simulation software have been a key driver in recognizing the ways of integrating architectural criteria with the structural performance of the pavilion. Furthermore, the comparison between the digital simulation of the architectural output and the final output, the pavilion itself, provides useful information to be considered and embedded in the future digital simulations. Overall, the research aims to illustrate the architectural possibilities of using concrete in a non-conventional way with limited resources and period of time by creating strong associations between computational design methodologies and digital fabrication processes.

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Figure 6
Final wall structure, detail displaying surface textures.