MESH MOULD: ROBOTICALLY FABRICATED METAL MESHES AS CONCRETE FORMWORK AND REINFORCEMENT

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ABSTRACT

The research project Mesh Mould explores the unification of formwork and reinforcement into one single, robotically fabricated construction system. An industrial robot is used to spatially “weave” a three-dimensional mesh, which acts as porous formwork during the process of concrete pouring, and is activated as reinforcement after the concrete has cured. In a first project phase a three-dimensional polymer extrusion process was developed allowing quickly assessing a wide range of mesh patterns and subsequently establishing an appropriate relationship of mesh morphology and concrete rheology. Whereas in the first phase, the loadbearing capacity of the polymer meshes was only of minor concern, the second phase of the project deliberately focuses on the structural performance of the meshes. Therefor an automated robotic wire bending and welding tool for steel meshes was prototypically developed, systematically tested and is currently undergoing further cycles of development. Concurrently a series of structurally differentiated metal meshes was fabricated semi-automatically and tested in destructive load tests. Particularly well performing mesh typologies subsequently inform the design of the next iteration of the robotic wire bending and welding manipulator. As such, the research aims to develop a fully automated in-situ robotic fabrication process for geometrically complex, loadbearing concrete constructions.

Key words: Digital design, robotic fabrication, formwork, reinforcement, non-standard concrete construction
INTRODUCTION

The Gramazio and Kohler Research group at the Chair of Architecture and Digital Fabrication at ETH Zurich, has over the past years explored the impact of robotic fabrication on architectural design and construction. The chair’s research points into the direction of a digitally informed and robotically materialized future of architecture. A novel, “digital materiality” [1], displaying a high complexity and sophistication digitally inscribed into the material, is rendered possible only through the dexterity of the robot. The research Project Mesh Mould follows that line of inquiry and investigates how the unification of the two most labour and cost intensive aspects of concrete structures, the formwork and the reinforcement [2], into one single, robotically fabricated construction system allows for a cost and material efficient fabrication of geometrically complex concrete constructions. The multitude of interacting parameters which are touching upon the diverse disciplines of architecture, robotics, material science, computation, mechanical-, and electrical-engineering has opted to develop the Mesh Mould technology in iterative cycles. Accordingly the report is structured along two consecutive phases. The first phase of the project focused on the development a generic robotic fabrication process, allowing to quickly produce and test a wide range of mesh morphologies and geometries. The experiments generated essential knowledge regarding the rheological behavior of concrete within the mesh and in defining an appropriate ratio of mesh aperture size and concrete viscosity.

1. Development of an automated robotic fabrication process for fast prototyping and subsequent evaluation [3].
2. Development of generative computational model as a design tool for topologically differentiated mesh morphologies.
3. Calibration of the relationship between mesh aperture size and concrete rheology [4].
4. Development of an appropriate concrete filling strategy.

A customized toolhead for the spatial extrusion of Acrylnitril-Butadien-Styrol (ABS), a thermoplastic polymer conventionally used for layerbased 3D printing applications, was developed. Key features of the extruder were an extrusion thickness of up to 3mm diameter, a temperature differential of 270 °C as well as an additional air-cooling mechanism with a capacity of 10 liter air per second. The latter allowed the instantaneous hardening of the thermoplastic, and thus enabled to spatially print complex freeform mesh structures (Fig 1-3). Despite the relative weakness of the ABS filament with a ultimate tensile strength of only 28 MPa [5], this generic extrusion process was found to be an effective way for short evaluation cycles of various mesh patterns upon their performance during the process of concreting. The experiments generated essential knowledge regarding the rheological behavior of concrete within the mesh and in defining an appropriate ratio of mesh aperture size and concrete viscosity,
However the targeted loadbearing capacity of the meshes can only be achieved by improving the yield strength of the mesh material itself. In this current, second phase of the project the research is devoted to developing an automated robotic fabrication process that builds up on the findings of phase one, but under additional consideration of the factual structural demands. Thus the goals of the second phase are defined as follows:

1. Development of a robotic tool head for processing filament with high yield strength, such as steel, synthetic-, or natural-fibers.
2. The fully automated robotic fabrication of several fully loadbearing mesh specimens for structural testing.
3. The exploration of the architectural design implication of such construction system.
4. The automated fabrication of a small architectural demonstration project, displaying the design implications and the structural potential of the system.

FIRST RESEARCH PHASE: INITIAL EXPLORATION INTO DIFFERENTIATED POLYMER MESHES AND EVALUATION OF CONCRETE FILLING PROCESSES

Preliminary concrete filling experiments showed that a self-compaction concrete with a slump of 19 cm (tested with a mini-cone with an upper diameter of 7 cm, lower diameter 10 cm, height of 6 cm) was clogging inside the mesh, preventing an even distribution of material within. This observation was attributed to an unfavorable ratio of exterior and interior mesh density. Whereas the triangulated interior structure was too dense (side lengths $a, b = 15$ cm, $c = 4$ cm) for the concrete to evenly distribute within the mesh, the triangulated exterior was found to be too open (side length $a, b, c = 4$ cm) to prevent the concrete from leaking out. Based on these findings two series of functionally differentiated mesh typologies were developed aiming to assure sufficient concrete flow inside the mesh while preventing excessive concrete leakage through the outer perimeter. The first series of meshes ($b \times h \times l = 15 \times 50 \times 60$ cm) was designed for frontal concrete filling. The experiments were conducted in collaboration with Sika Technology AG using a Sika MonoTop 412 N repair mortar [6] for wet spray applications. The mortar, with an adhesive strength $\geq 2.0$ MPa is particularly well suited for vertical and over-head applications. The mesh specimen
displayed larger triangular apertures on the front than on the back. The open front was designed to allow the Shotcrete to enter the mesh whereas the denser back aimed to prevent the concrete from shooting through (Fig. 4). One half of each mesh was filled by wet-spraying the mortar with a 12 mm refurbishment nozzle and an air pressure of 4 bar from a distance of approximately 40 cm (Fig. 6), the other half was filled without use of the nozzle, directly pressing the mortar through the mesh perimeter utilizing the mere pressure of the concrete pump (Fig. 7).

![Fig. 4: Two Mesh typologies, a and b, for frontal filling, each with larger apertures on the front (left) and denser apertures on the back (right). Mesh a consists of a triangulated front with a side length of a, b, c = 4 cm and triangulated back with a, b = 2 cm and c = 4 cm, Mesh b consists of a triangulated front with a side length of a, b, c = 6 cm and triangulated back with a, b = 3 cm and c = 6 cm.](image)

A second series of meshes (b x h x l = 20 x 80 x 60 cm) was designed for top-wise filling. Holcim Singapore supported the testing and developed an application-specific concrete with a low water-cement ratio and low slump flow; vibrating with a poker vibrator was required after filling (Table 1, Holcim).

Table 1: Two Concrete mixtures used for filling ABS and metal meshes

<table>
<thead>
<tr>
<th></th>
<th>Holcim mix</th>
<th>ETHZ IFB¹ mix</th>
</tr>
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<tbody>
<tr>
<td><strong>Water-cement ratio</strong></td>
<td>0.36</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Ordinary portland cement</strong></td>
<td>450 kg/m³</td>
<td>500 kg/m³</td>
</tr>
<tr>
<td><strong>Undensified silica fume</strong></td>
<td>-</td>
<td>43.5 kg/m³</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>160 kg/m³</td>
<td>169 kg/m³</td>
</tr>
<tr>
<td><strong>Aggregates of grain size 0-4 mm</strong></td>
<td>713 kg/m³</td>
<td>705 kg/m³</td>
</tr>
<tr>
<td><strong>Aggregates of grain size 4-8 mm</strong></td>
<td>-</td>
<td>1008 kg/m³</td>
</tr>
<tr>
<td><strong>Aggregates of grain size 10 mm</strong></td>
<td>1020 kg/m³</td>
<td>-</td>
</tr>
<tr>
<td><strong>Modified lignosulphonate based retarder</strong></td>
<td>1.58 kg/m³</td>
<td>-</td>
</tr>
<tr>
<td><strong>Polycarboxylate ether superplasticizer</strong></td>
<td>3.65 kg/m3</td>
<td>4.32 kg/m3</td>
</tr>
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¹ The recipe was developed by Lex Reiter from Institute for building materials (IFB) at ETH Zurich
The mesh design of the second series followed two main strategies: Firstly the introduction of filling channels within the mesh (Fig. 5 a-c), and secondly a general decrease of density of the interior structure (Fig. 5 d-f). For both experimental setups the evaluation parameters were defined as follows:

1. An even distribution of concrete within the mesh without the occurrence of aggregate nests or voids.
2. A protrusion rate of the concrete from inside through the outer perimeters of the mesh of approximately 1 cm during vibrating.
3. The mesh’s shape stability under the process of filling, and under the wet load of concrete.

![Mesh typologies for top wise filling with apertures ranging from a, b, c ≥ 2cm ≤ 4 cm.](image)

**Findings:**
When filling the meshes frontally via the mere pressure of the concrete pump, a high pressure led to considerable deformations of the mesh up to 1.5 cm, particularly noticeable at the corners and edges. Furthermore the concrete did protrude only approximately half way from one side of the mesh to the other, suggesting that the mesh should rather be filled from both sides. Moreover the distribution of the viscous concrete paste was not consistent and showed the occurrence of voids up to a diameter of 1.5 cm around parts of the horizontal interior mesh structure.

The wet-spayed Shotcrete on the other hand consistently protruded through the front of the mesh without damaging it. In order to prevent the concrete from shooting through however, the aperture size on the back side should be further reduced to a size of at most 1.5 cm for all triangle sides. Furthermore, both frontal filling methods imposed unsymmetrical loading on the mesh during the process of filling. At a larger scale and without additional scaffolding this is likely to cause deformations of the overall structure during filling. The concrete paste allowed a good workability during the manual troweling process and enabled a smooth surface finish (Fig. 8, bottom).
With regards to the top wise filling, the partially missing interior structure in regions of the flow channels (Fig. 5a, b, c) noticeably weakened the overall stability of the specimen. The wet load of concrete caused buckling and led to deformations up to 3 cm in the channel area. Furthermore, the concrete did not distribute uniformly from the channels throughout all regions of the mesh, causing voids of up to 2 cm diameter. A general, even reduction of the horizontal interior structure on the other hand worked well for the filling and vibrating process. Moreover, the introduction of a tetrahedral geometry of the outer perimeter (Fig. 5f) significantly improved the structural performance during the filling and vibrating process. Furthermore the tetrahedral perimeter increased the flow resistance and showed a positive effect on the protrusion rate of the fresh concrete (Fig. 9-11).
SECOND RESEARCH CYCLE: IMPROVING THE STRUCTURAL CAPACITY

In order to meet the goal of activating the meshes not only as formwork, but at the same time as structural reinforcement, two possible lines of inquiry were identified. Firstly, the co-extrusion of a tension active filament within a polymer matrix, as for example with alkali-resistant glass fiber, carbon fiber, aramid or basalt [7], and secondly the substitution of the polymer filament with thin, continuous steel wire (d ≤ 3mm). Both options display a unique set of characteristics with specific advantages and disadvantages. Despite being prone to corrosion, metal wire displays a multitude of advantages. The compound of steel and concrete, for example, is a well-established material system with good mechanical bonding and very similar expansion rates. Steel wire is, compared to the high-tech fiber compound, a fairly cheap and almost universally available material [8]. Its ability to be monolithically joined through discharge welding makes the connections between the layers simple and straightforward, even for small diameters [9]. Another major advantage can be accounted to the fact that steel can be deformed plastically at fast rates without having to thermally activate it. Although, for the current research phase the material question was decided in favor of steel wire, fiber reinforced polymers remain a promising path for follow-up research.

TOOLING AND PROCESS ENGINEERING

Based on both, the insights won throughout the previous ABS extrusion experiments, and on the decision to focus the coming research phase on processing metal wire, a concept for a robotic wire bending and welding manipulator was developed and has evolved over various iterations. The initial concept for a wire deformation mechanism was developed (Fig. 12a) and was prototypically realized and tested with commercially available pneumatic actuators (Fig. 12b). The integration of all required functionalities, including electronic linear position feedback actuators, retractable components for collision avoidance and a discharge welding compatible wire bending mechanism resulted in a manipulator size of 10 x 8 x 22 cm (Fig. 12c), appropriately small and agile for the realization of filigree architectural geometries.

Fig. 12: Evolution of wire bending-welding manipulator.
The functional principles of the manipulator in its current state are described in greater detail below:

1. The upper wire is clamped by two outer brackets (Fig. 13 a).
2. The linear actuator extends to the calculated length (depending on the surface curvature) and bends the wire into a “V” shaped configuration (Fig. 13 b).
3. The upper wire touches the lower wire and an electrical impulse is discharged, spot welding the two wires together.
4. The outer brackets open up again and a part of the clamping mechanism rotates 90 degree inwards in order to avoid collision with the previously bent part (Fig. 13 c).
5. The tool head moves to the next position and the routine repeats.

![Fig. 13](image.png)

Fig. 13: Bending and welding cycle.

**Tooling: Future challenges**

During extensive fabrication tests the current bending-welding manipulator has revealed several weak spots for further improvement. Among the most challenging future developments are:

1. The incorporation of a wire pre-straightening mechanism.
2. The design of a robust wire alignment mechanism within the welding electrode in order to guarantee flawless welding connections.
3. Sufficient dimensioning of the components for processing wire up to 3mm diameter.
4. A wire guidance mechanism for the horizontally oriented wires.
5. Further actuation of collision-prone components.

In order to be able to quantify the structural performance of the metal meshes as reinforcement, a robust and reliably repeatable fabrication process is of paramount importance. As the demanded process stability cannot be guaranteed in the tool’s current iteration, the bending-welding manipulator presently undergoes further development, specifically addressing the above mentioned issues. Meanwhile a semi-automated fabrication process was developed, allowing to reliably fabricate various mesh samples for concrete filling and structural testing. In this intermediate
fabrication setup, the robot three-dimensionally bends single mesh layers, which are subsequently assembled and spot welded manually. The identification of mesh typologies that are, next to being formwork, additionally complying with the demands of structural reinforcement, directly feeds back into the refinement and further specification of the tool.

**MESHES FOR INITIAL STRUCTURAL LOADING**

On the basis of the successful mesh typologies of the first research phase, a series of rectangular metal meshes (b x h x l = 7 x 9 x 30 cm) with different patterns was fabricated (Fig. 14). The primary aim of this initial structural test was to identify certain particularly well performing characteristic of the mesh, which in turn would inform the further development of the robotic bending-welding manipulator.

![Fig.14: Robotically fabricated meshes for structural loading.](image)

The main directions followed in the development of the test specimen were:

1. Increased spatiality through tetrahedral perimeter and spatially diagonal interior structure (Fig. 15, v1, v2).
2. Increasing number of the horizontally running wires (Fig. 15, v3).
3. Vertical build-up as an alternative to the horizontal layout (Fig. 15 c, v4).
4. Varying the density of mesh apertures, from the smallest size producible to the largest aperture size capable of holding the concrete (Fig. 15, v5 and v6).
5. Perimeter layering of the mesh, double layered perimeter (Fig. 15, v7).

![Fig.15: Mesh typologies, versions v1 - v7.](image)
With regards to the concrete, the previous mixture of phase one was slightly modified (Table 1, ETHZ IFB). The meshes were filled from atop, using formwork only on the two open ends and at the bottom of the mesh, leaving the mesh faces with the triangulated pattern exposed. Other than in previous trials a vibrating table was used to consolidate the samples. The concrete coverage was 1 cm on each side, except on the open mesh ends, resulting in a sample size of $b \times h \times l = 9 \times 11 \times 30$ cm. The probes cured for 14 days in a curing chamber with a relative humidity of 95 %. A three point bending test, with two supports in a distance of 21 cm and a centered load was performed with a movement speed of 0.01 mm/sec (Fig. 16). An additional beam (v8) with no reinforcement served as a reference.

![Displacement as a function of the sample's loading force.](image)

Fig. 16: Displacement as a function of the sample's loading force.

The mesh volume fraction varied among the different mesh typologies (Fig. 17) and was relatively low compared to a conventional steel reinforced concrete-, or ferrocement-structures [10]. For the sake of comparability an equal mesh volume fraction was initially considered, but finally discarded due to the multifunctional requirements of the mesh. The structural performance is only one parameter among others, as for example, the concrete distribution inside the mesh, the concrete protrusion rate through the outer perimeter, the roughness of the surface structure as a basis for troweling, as well as the degree of complexity for an automated fabrication process. In that regard the load test revealed that a mesh with a double perimeter (Fig. 17, v7) and a higher volume fraction had a lower structural performance compared to a single layer mesh with additional horizontals (Fig. 17, v3), however, with regards to the concrete protrusion rate, for example, the layered buildup of the latter showed significant advantages during the process of concrete filling.
The force displacement behavior of meshes v1, v3, v7 (Fig. 16) displayed a significant yield plateau with an increasing load capacity after the first crack appeared. Additionally mesh v3 showed the appearance of a second crack, indicating a substantial loadbearing behavior of the mesh after the appearance of the initial crack. This observation is supported by a very pronounced plateau of that particular mesh typology. In contrast to the inclining yield plateaus of v1, v3 and v7, the typologies v2, v5 and v6 displayed a noticeable drop of load bearing capacity after the appearance of the first crack, indicating that the meshes were unable to compensate loads beyond that force. The force displacement behavior (Fig. 16) in relationship to the mesh volume fraction (Fig. 17) suggests that a minimum volume fraction of 1.4 % is necessary in order for the meshes to act as reinforcement. Whereas this observation is valid for meshes with a horizontal build-up, it does not comply with the behavior of the vertically buildup mesh v4. Despite a mesh volume fraction of 1.3, the specimen displayed a behavior very similar to the reference beam v8 without any reinforcement. This brittle behavior can be attributed to the weak welding connections, combined with the complete absence of continuous horizontal wires. The diagonal interior structure of specimen v2 does not contribute to the structural performance under this specific load case, could however be activated as helical reinforcement in particularly high stressed elements.

**CONCLUSION AND NEXT STEPS**

The physical experiments of phase one and two have verified the underlying assumption, that formwork and reinforcement can be effectively combined into one robotically fabricated construction system. The elements of the research, namely the concrete recipe, the mesh typology and the robotic fabrication process, are strongly interlinked and can only be looked at in a mutually depending manner. The challenge of the future research will be to pinpoint the “sweet spot” at the intersection of the robotic mesh fabrication, the performance during filling, the concrete workability during troweling, the final surface quality and the mesh’s structural performance as reinforcement. With regards to the tool developments some significant conclusion can already be drawn from the initial load tests: The minimum mesh volume fraction above 1.4 % implies that certain mesh typologies, as for example v5 and v6, can only be activated as reinforcement by increasing the diameter of the wire. This in turn would result in a bulkier bending-welding manipulator and a higher percentage of
steel which does not act as reinforcement (e.g. the horizontal interior structure). Therefore it seems more appropriate to develop the next version of the bending-welding manipulator with a particular emphasis on the ability to lay additional horizontally aligned wires. Besides structural considerations the filling experiments from phase one identified a slightly structured mesh surface (e.g. mesh v1) as beneficial for the concrete filling-, and subsequent troweling-process. Following up on the immediate phase of tool re-development a next series of experiments will direct the focus again towards the architectural implication of the fabrication system. Thus a wider set of geometries will be tested, including vertically oriented elements and continuous transitions from vertical to horizontal building elements. For a better workability and an increased stability of the concrete, especially on such sets of geometry, a modification of the structuration rate in the early age of the concrete will have to be considered [11].

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REFERENCES


