MESH MOULD: AN ON SITE, ROBOTICALLY FABRICATED, FUNCTIONAL FORMWORK

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Keywords: Robotic Fabrication, Functional Formwork, Digital Concrete, Concrete Reinforcement, 3D Printing

ABSTRACT

Digital fabrication with concrete has become a highly interesting topic due to the potential for freeform architecture and efficient material placement, with major strides in its development taking place in the past few years. However, reinforcement remains problematic, as current technologies rely mostly on post-hoc placement and infill. In this paper, we present the Mesh Mould, a digital fabrication technology unifying formwork and reinforcement, wherein a mobile robotic arm with a specially designed end effector bends, welds, and cuts steel reinforcement to additively manufacture a digitally designed mesh either onsite or in a prefabricated environment. This mesh is subsequently infilled with concrete and finished with a cover layer to serve as a freeform reinforced concrete structural element. Research challenges for various fields such as robotics, concrete technology, structural engineering, as well as architecture are presented, highlighting the multidisciplinarity of the project and serving as a microcosm of how synergies between disparate fields can be exploited within this burgeoning area of research.

1. INTRODUCTION

From the perspective of architects and engineers, reinforced concrete is a fantastic material, highly appreciated for its ability to sustain high tensile and compressive loads, while being relatively low cost and widely available. Additionally, the freedom of shape and aesthetic quality are great assets in design; therefore its use has a longstanding tradition in architecture. Whether we talk of the expressive and sculptural *Béton Brut* constructions of Le Corbusier, the elegant and structurally efficient designs of Eero Saarinen or the intricate structural articulations of Pierluigi Nervi's rib constructions, all these reference structures represent a formal language characteristic of concrete as a mouldable construction material.

To better exploit this potential in a cost effective and environmentally friendly way represents one of the greatest challenges posed to concrete technology today. Indeed, the desire to explore the sculptural dimensions of concrete has tremendously increased over the last decade or two, not the least due to the advent of digital design software, which itself is inherently inclined towards curvilinear geometries [1]. However, building such structures entails very important costs in terms of formwork. For example, for doubly curved surfaces, costs can reach up to 75 % of the final structure`s cost [2]. Moreover, such formwork is usually produced as one of a kind moulds only to be used once and that cannot be recycled. Consequently, current technologies for producing non-standard architecture in reinforced concrete are hardly sustainable economically or environmentally, even if the built structures are highly efficient.

The Mesh Mould technology presented in this paper specifically attacks these limitations, proposing a novel construction process based on digital fabrication to produce complex reinforced concrete structures. It contrasts with most other digital fabrication approaches in the sector [3] since it intrinsically incorporates continuous steel reinforcement, which is crucial for the load bearing function that non-standard structures are most often expected to offer in architecture.

This paper presents the result of a multi-disciplinary research effort involving architects, structural engineers, roboticists and material scientists. It presents the specific technological challenges that had to be overcome using specialised knowledge of each of these fields. Ultimately, it presents a paradigm shift for the production of complex reinforced concrete structures. As such it has already attracted a lot of attention (finalist of the Swiss Technology Awards [4]) and is planned for production of the first full scale demonstration of an on site, robotically fabricated load bearing complex reinforced concrete structure described at the end of this paper.

2. MESH MOULD CONCEPT

The key feature of the Mesh Mould process is to unify the reinforcement and formwork production into a single and robotically controlled fabrication system. As such, Mesh Mould relies on an industrial robot, equipped with a specially designed end effector to automatically fabricate a dense, 3-dimensional mesh structure, either in a prefabrication setting, or on site. Following the mesh fabrication, fresh concrete is infilled, and a cover layer is applied and finished. By pouring the concrete in one process the layering issues inherent to other digital fabrication processes can be reduced or eliminated. Additionally, activating the mesh as reinforcement renders it as a functional stay-in-place formwork, making the process inherently waste free. As such, the robotic fabrication process presented facilitates a waste free fabrication of freeform loadbearing concrete elements, where complex geometries can be fabricated at no additional cost.

3. MESH DESIGN AND PRODUCTION

The Mesh Mould technology was developed in two consecutive stages. A first phase investigated the interrelationship of mesh topology, cell size, and the rheological behaviour of the fresh concrete within the mesh. During that stage, model meshes were produced with a polymer extrusion process reported elsewhere [5]. Here, we report on the second phase, in which steel meshes have been produced with structural activation as the primary focus. In this context, Ferrocement represented a reference system as explained below. After recalling the background about this system, we present the robotic process that we developed to produce improved steel meshes to deliver enhanced structural performance.

3.1. Ferrocement as model

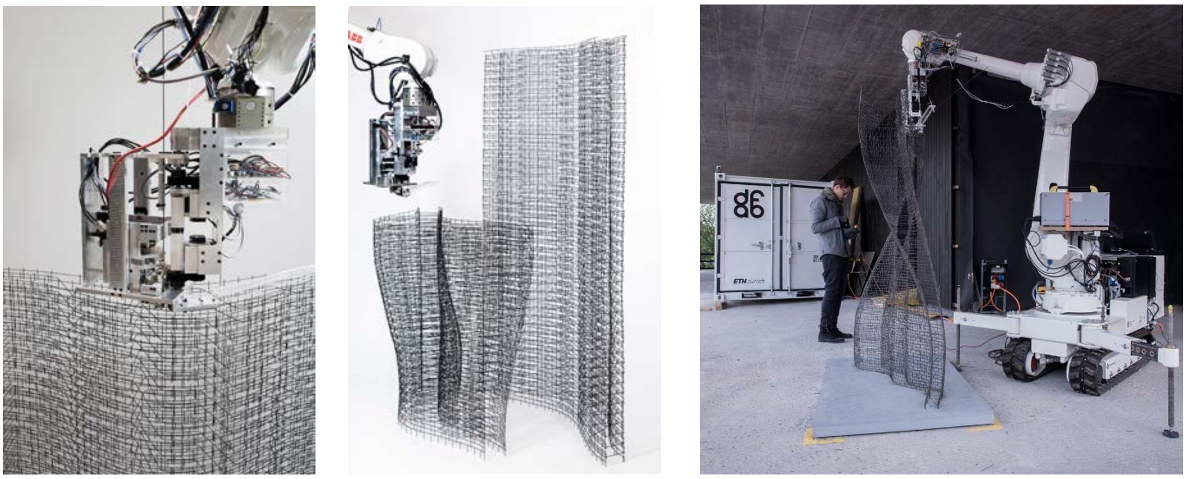
The first use of fine metal meshes as concrete reinforcement dates back to 1847 and marks the birth of reinforced concrete itself. This is due to Joseph-Louis Lambot, who constructed a small boat using wire meshes and a matrix of fine cement mortar which he pressed through the mesh in order to construct a thin, watertight hull [6]. Lambot coined his invention “Ferciment”, or “Ferrocement” in English, and patented it 1855. However, in the years to follow, the initially slender Ferrocement constructions successively developed into thicker elements and became what is known today as reinforced concrete. Only in the 1940s did Pier Luigi Nervi rediscover Ferrocement, realizing the possibility of this system for materially efficient and structurally performant constructions that could further be optimized by intelligent use of shape [7]. The major drawback, however, was that the prefabrication involved raised the labour costs so high it rendered this “artisanal” construction system economically ineffective [8]. Today however, considering robotic fabrication processes for such meshes, Nervi`s construction system appears in a new light, in which the system`s efficiency and the reduction of formwork material remain unchanged. Importantly, it also takes on additional structural efficiency thanks to the dexterity and precision of robotic fabrication.

3.2. Robotic fabrication of the meshes

The decision to change the fabrication process from the spatial extrusion of polymers to the robotic processing of steel wire also required the reconsideration of the mesh topology itself. Whereas initial automation attempts aimed to translate the continuity of the polymer extrusion process to the steel wire based process [9], it was realized that a discretization of the mesh into continuous horizontal wires and discrete vertical wire elements would allow roboticization of the fabrication process by developing a customized self-contained special purpose robotic end effector. This end effector is attached to a mobile robotic manipulator, and consists of a front part for bending the continuous horizontal wire and a rear part, which incorporates a clamping, a wire feeding, a pneumatic cutting and a resistance welding mechanism (see Fig. 1a). By moving the robotic end effector through space, the robotic arm (a standard industrial manipulator) achieves the overall geometric modulation of the process, allowing for precise control of the 3D form of the mesh. This process is well suited for both in situ construction and prefabrication settings.

One of the key challenges in the robotic fabrication of steel meshes stems from inherent imprecision in the process. Due to a number of reasons (e.g. residual stress) the placed wire will show some positioning inaccuracy with respect to the CAD design. Such error must be registered by appropriate sensing strategies and fed back into the design control and production pipeline. Otherwise, if left unchecked, such imprecisions can have a negative influence on structural performance. The high level specifications derived from the robotic fabrication process greatly depend on the diameter of the wire used, but also include details such as minimum and maximum cell sizes, minimum thickness of the mesh, curvature, etc. These specifications constrain the mechatronic design solutions and their practical implementation in the form of the robotic end-effector.

Again all these aspects are relevant for the ultimate structural performance in service as well as for the placing of concrete in the mesh and its corresponding mix design. The digitalization of the robotic fabrication process and its associated toolchain offers new opportunities for quality control and data driven approaches (e.g. registering the quality of the welds, placement of the wiring, etc). More details about the overall robotic setup, the robotic fabrication process and a detailed description of the end effector`s functional principles and digital control routines are given elsewhere [10].



(a) (b) (c)

Fig. 1. (a) Mechatronic tool head designed to cut, bend, and weld steel wires. (b) Single curved 2 m mesh and double curved 1 m mesh both constructed by In Situ Fabricator. (c) Double curved 1 m mesh

3.3. Sample meshes

In this paper, we report on a series of three steel wire meshes that were fully automatically fabricated with the aforementioned robotic setup. For all meshes a plain 2.5 mm black annealed steel wire was used. The first mesh describes a single curved geometry with a varying cross-section ranging from 8 to 25cm, and was built up to a height of 2 meters. A second, more complex mesh was produced with curvatures in both principal directions to demonstrate the geometric versatility of the robotic fabrication setup. This mesh was built up to a height of 1 meter. Both meshes (see Fig. 1b) were subsequently used for concrete filling experiments, which are described in the next section.

Whereas the previous two meshes were fabricated in the controlled environment of the laboratory, the third mesh was produced in the unstructured environment of a building site. Here the mobile manipulator, called the In Situ Fabricator, produced a two meter high, double curved mesh with various curvature radii and cantilevers up to 50 cm (see Fig. 1c). Similar to the previous meshes, also this mesh contained an average mesh cell size of approximately 4 cm in the horizontal direction and 2.3 cm in the vertical one.

4. CONCRETING STRATEGIES

4.1. Retention ability in the mesh

At first glance, concreting the mesh successfully requires a concrete that will stay within the mesh, having achieved a sufficient compaction without having flown out. This is not a trivial problem and therefore an understanding of how the mesh contributes to flow resistance is needed. As a first step in studying this problem, a series of tests were performed with standard mortars prepared using the following proportions normalized to 1 L: 0.5 kg CEM I 42.5, 1.3 kg sand from 0-2 mm, and 0.3 kg water. An identical mix with 2.9 g RMH 182-4 polymer fibres added was also prepared. The density of the mortars was approximately 2100 kg/m^3, and the spread flow tests for the materials with and without fibres yielded results of 270 and 360 mm, respectively, giving yield stresses of approximately 730 and 290 Pa [11].

To better understand how the filling height may cause the flow of mortar out of the bottom part of the mould we designed two simple tests. In the first of these tests, a cylindrical mold with a 150 mm diameter and a 50 mm height was constructed with a regular 2D mesh at its base having 25x25 mm cells and 2 mm wire diameter. A platen of the same diameter was mounted to the universal testing machine and pushed downward to determine the force required to push the material through this mesh. These experiments were carried out at a constant speed of 0.2 mm/s.

An alternative test, somewhat easier to set up was considered. It is based on pulling out a mesh embedded in the mortar and measuring the force needed to do this. In this case we used meshes 150x115 mm with the same cell size and wire diameter as above. These meshes were oriented vertically and embedded in the centre of a 150x150x150 mm mold filled with mortar. They were then pulled out at a constant speed of 0.5 mm/s and the force needed for this was recorded with a universal testing machine. Both types of tests were carried out after various resting times to observe if time dependent structural build up could be a factor.

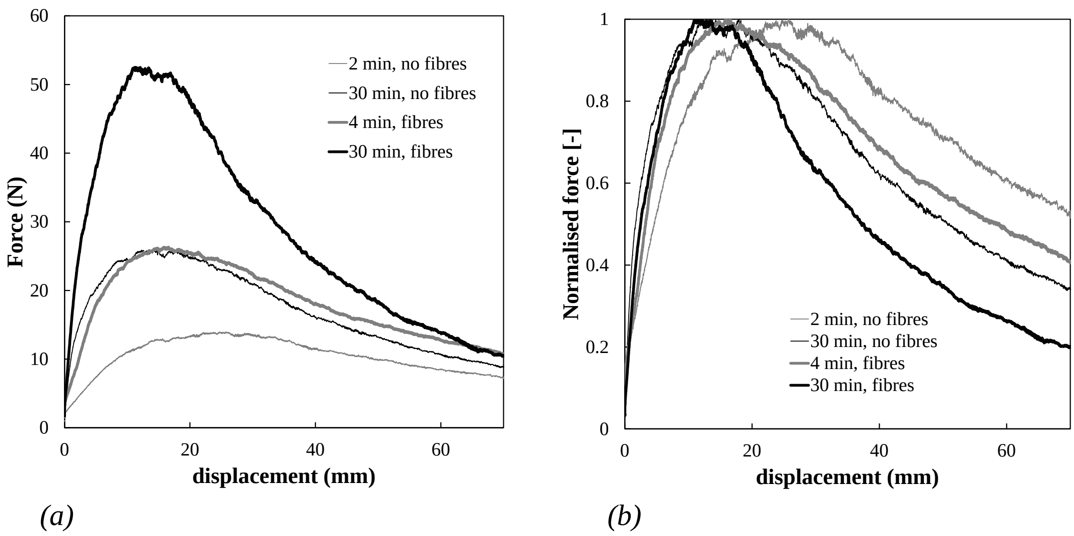


Fig. 2. Pull out test for mortars, with and without fibres, on 25x25 mm mesh with 2 mm wires. (a) raw data (b) data normalized by the peak value of each data series. The similar values of the curves suggests that the initial evolution is a property of the test rather than the material.

The results of the pullout tests are displayed in Fig. 2a, and it can be observed that the force evolves to a maximum during the test. In Fig. 2b each curve has been normalised by its peak value from Fig. 2a, which collapses all curves upon one another in the range where the force increases with displacement. This suggests that the slope of the initial load increase can be a useful material characterization parameter. In fact, it turns out that the ratio of the yield stress with and without fibers (2.5) is very similar to the ratio of initial slopes after 2 minutes rest (2.75), which is best representative of the resting time applied before the yield stress measurements. However, the ratio of slopes with 30 minutes resting time gives values that are also in range of the yield stress ratio (1.9). This suggests

that, in first order, the pullout test is governed by the yield stress, which is modified by the presence of fibres and resting time.
The results of the push through test are shown in Fig. 3a. They show a monotonic increase during the test, which contrasts with the pullout test. Here we choose to normalise each data series by the initial slope of the pullout test, that was previously identified as a material property. As shown in Fig. 3b, all the data series collapse to a very similar trend, suggesting again that the measured values are related to the yield stress of the material. The monotonic increase, however, suggests that other mechanisms could be at play as well, such as jamming. To support this claim, we can state that an independent experiment with a very low yield stress self-compacting concrete was carried out. In this case we obtained a plateau, which is more consistent with what would be expected in this test in absence of jamming. Beyond a certain displacement the force increased slightly, which is consistent with jamming statistics as analysed using game theory [12].

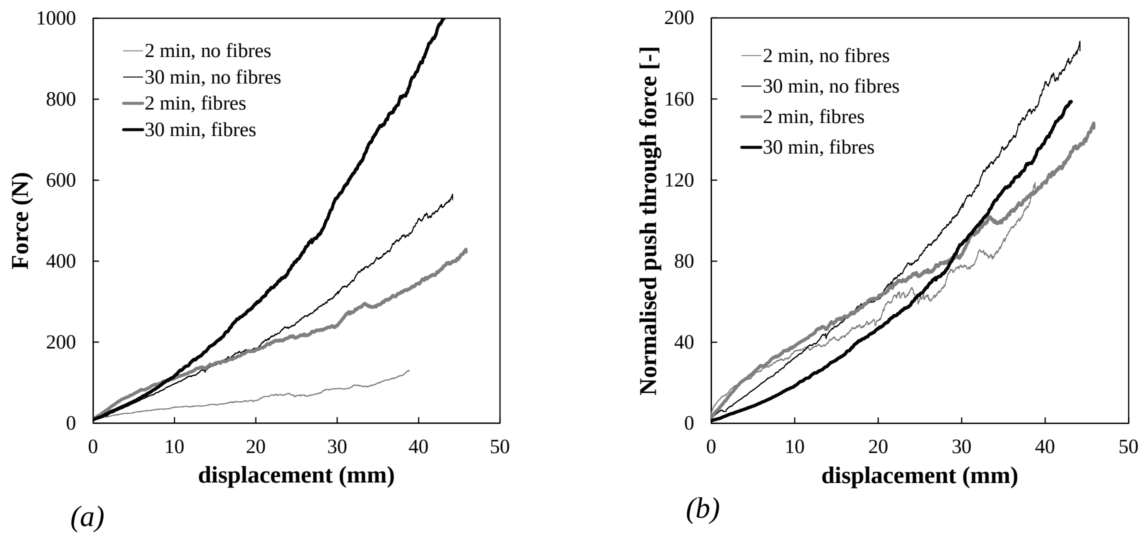


Fig. 3. Push through tests of mortar, with and without fibres, on 25x25 mm mesh with 2 mm wires. (a) raw data (b) Results of (a) normalised by initial slopes of pullout test.

Overall, these results indicate that for the selected combination of mesh size and mortar mix design, the ability of the mortar to flow through the mesh is governed by its yield stress and jamming propensity. Quite conveniently both factors appear to be separable from each other since a master curve is obtained in Fig. 3b. In this context, the pull out test appears as a convenient way to evaluate yield stress after waiting times that may render other simple tests and spread flow inadequate. This role of yield stress implies that past research on formwork pressure and thixotropic build up may be used to understand one aspect of the flow out propensity of mixes in these meshes. Independently of this, blocking appears as an effective strategy to enhance retention in these meshes, and optimizing mix designs with consideration of fibre and aggregate grading should offer effective solutions for filling meshes, without having the material flow out of them sideways (see for example Fig. 4b).

4.2. Filling ability of the mesh

Two filling tests carried out with steel meshes are reported here. The first mesh, a single curved mesh of about 2 m height and 10 to 35 cm in thickness, was filled using Sika Monotop 412N mixed in a single batch of 250 litres. The mesh was filled by hand to the full height of 2 meters, with no issues of excessive leakage. The yield stress, measured via spread flow, is calculated to be 800 Pa, similar to the mix with fibres presented earlier. The material that protruded out from the mesh was smoothed by hand using a trowel. After hardening for some days, this mesh was then finished using fine grained cement render, also by hand. The final mesh can be seen in Fig. 4a.

The second filling test was performed, also with Sika Monotop 412N, on a 1 m high double curved mesh that varied in thickness from 10 cm to 30 cm, and with up to 10 cm of overhang. In this test a pump was deployed to fill individual channels within the mesh structure, depicted in Fig. 4b. In this case, the internal filling was much smoother, with minimal compaction needed. In a second step, pumping through the mesh structure from the side was also tested, with clearly more compaction needed in this case. This supports the claim made above that the 3D mesh design can be optimized to facilitate a good filling of the mesh with minimal compaction needed if the material is cast in its centre rather than pushed in from the sides.

Concerning the compaction, this was tested with a vibrating needle and caused the concrete to flow out more than desired, however without critically affecting the overall filling process. As in the previous experiment the outer surface of the object was manually finished using a fine cement mortar (see Fig. 4c). In both filling tests, however, there was difficulty in maintaining a cover layer of constant thickness, with much of the material falling off under the shear provided by the final hand finish.

(a) *(b)* *(c)*

Fig. 4. (a) 2 m single curved meshed with finish. (b) Concreting process of 1 m double curved mesh using pump. (c) Finishing of a double curved sample.

From a practical standpoint, it appears that a lower yield stress concrete should be used for filling and that the mesh structure must be optimised in 3D for this. Additionally, it can be expected that improved mix designs targeting jamming on the side of the mesh may greatly enhance the quality of compaction while keeping the mortar in the mesh. Finally, for the cover layer, a much higher yield stress material such as shotcrete should be applied to form the outside layer. Questions of the timing of the application of this cover layer and pre-treatments to enhance its adhesion still need to be examined.

5. MECHANICAL BEHAVIOR

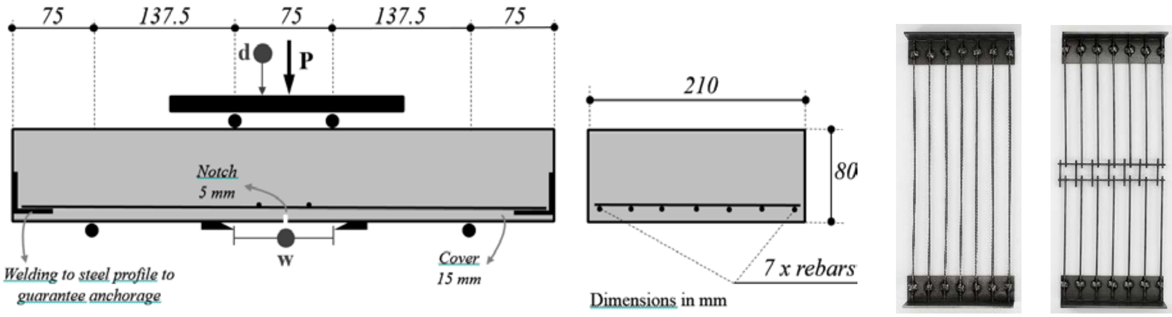
In this section, we examine the basic mechanical performance of concrete samples reinforced with the type of meshes described above. All tests presented in this section are done on samples containing on each side and in each direction at least 0.5% steel wires relative to the total concrete section. As explained in the next section, this should be enough to achieve a ductile behaviour if wires perform similar to conventional continuous reinforcement.

First of all, different reinforcements of various diameters and suppliers were tested to assess their properties, particularly their ductility. This is important since small diameter wires are typically cold worked and coiled, which may substantially reduce their ductility. In fact, the wires used in the preliminary mechanical tests, with a yield stress of approximately 700 MPa, had a strain at maximum load below 1.5%, much less than the usually required minimum ductility of structural steel or reinforcement. In future tests, only wires that comply at least with the requirements of ductility class A according to Eurocode 2 (EN 1992) [13] will be used.

The capacity of the welds was rigorously tested as well. Weld strengths of 80% of the wire shear strength could be reached without weakening or reducing the ductility of the wires, proving their viability for structural purposes. New experiments are planned to determine the possible increase of the weld strength without impairing the strength and ductility of the wires.

Having proved the feasibility of the welds, reinforced concrete samples were tested using the 4-point bending configuration and geometry shown in Fig. 5a. The samples were cast and vibrated in conventional formwork to avoid artefacts caused by inadequate compaction. The mesh was placed only in the tensile side, with a minimum cover of 15 mm. This cover will be required for the full scale demonstrator described in the last section, with an exposure class XC2 and structural class S2 according to Eurocode 2 (EN 1992) [13].

With these tests we studied the role of mesh anisotropy when using the same diameter and cell size in both directions. Indeed, the meshes are characterised by continuous wires in one direction, connected by short wires and structural welds. The meshes produced by the robotic end effector were simplified for the preliminary test series to reduce the variables that could impact the mechanical behaviour and get a better insight in the structural behaviour. Fig. 5b and Fig. 5c show the mesh configuration used when analysing the tension acting in the continuous wires and in discontinuous welded wires, respectively. Only in the latter case, one section of short welded wires was disposed at midspan. Further to the mesh anisotropy, we studied the difference between using plain and ribbed wires of similar diameters (3.8 and 4.0 mm respectively). The specimens are labelled with two letters. The first letter indicates whether the meshes are carrying tension in the direction of the continuous (C) or discontinuous (D), welded wires. The second letter indicates whether the wires were ribbed (R) or smooth (S). As an example, sample C-R had ribbed wires and was under tension in the direction of the continuous wires.

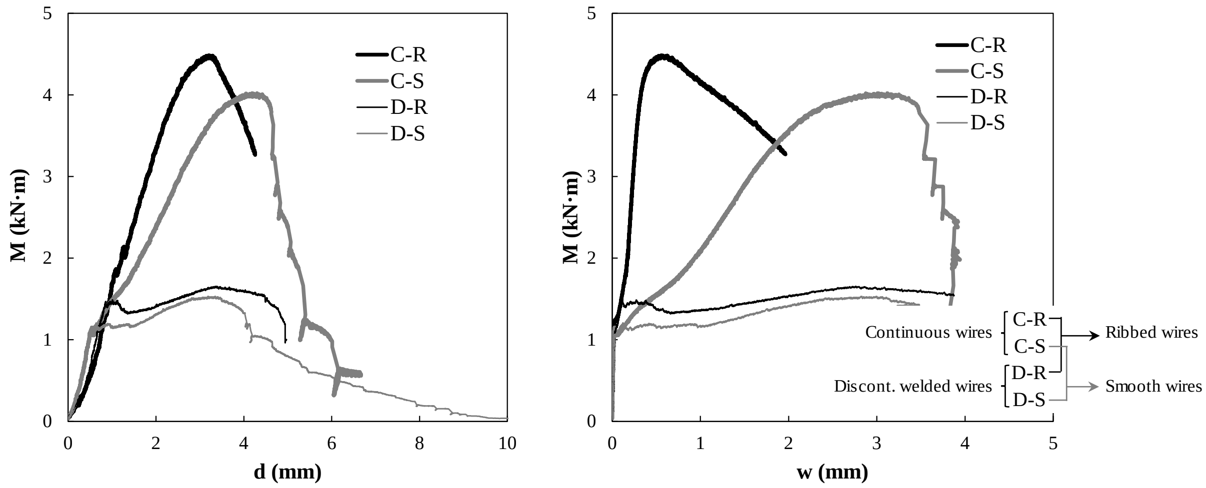


(a) *(b)* *(c)*

Fig. 5. (a) Test set up and instrumentation for 4-point bending tests of reinforced concrete samples. (b) simplified tested mesh for continuous wires. (c) simplified tested mesh for discontinuous (but welded) wires.

Bending moments, deflections and crack opening measured in the central notched section are shown in Fig. 6. A very good performance was observed in the continuous direction, with strain hardening after concrete cracking regardless of the type of wires. However, only very limited plastic deformations were observed at the peak load, presumably due to the limited ductility of the wires. This issue will be reassessed in future experiments using wires fulfilling minimum ductility criteria as mentioned above. For the specimens transferring the tension between wires through structural welds, strain hardening was observed after cracking as well, but the maximum load was much lower than in the direction of continuous wires. The strength was limited by yielding of the transverse connection wires that are subjected to combined shear and torsional loading due to the load transfer between welded wires (Fig. 7a) separated in the transverse direction. The torsional action is likely to be highly dependent on the localization of the failure and may therefore have been biased by the simplified meshes tested in this preliminary series, prone to localize the damage in the notched middle section. Further tests, currently under evaluation, have addressed the behaviour of meshes without these simplifications, showing a distributed cracking. Consequently, the strength in the direction of the discontinuous welded wires achieved up to 60% of the strength in the direction of the continuous wires, and it is anticipated to further improve this behaviour in future tests.

Concerning the effect of the wire types, Fig. 6a shows a slightly higher stiffness for the ribbed wires, caused by the slightly larger cross section and the greater influence of tension stiffening for the ribbed wires. Furthermore, a significant difference was observed in the cracking behaviour in the longitudinal direction (Fig. 6b), with much more distributed cracks and correspondingly smaller crack openings for the ribbed wires (Fig. 7b), contrasting with single and wider cracks obtained with the smooth wires. Hence, in terms of crack distribution, ribbed wires may offer a possibility of enhancing the mechanical behaviour of Mesh Mould structures. However, the benefit is limited to the direction with continuous wires; the cracking behaviour of ribbed and smooth wires is similar for the discontinuous direction where they are welded.



(a) *(b)*

Fig. 6. Results of 4-point bending tests: (a) bending moment-deflection and (b) bending moment-crack opening.

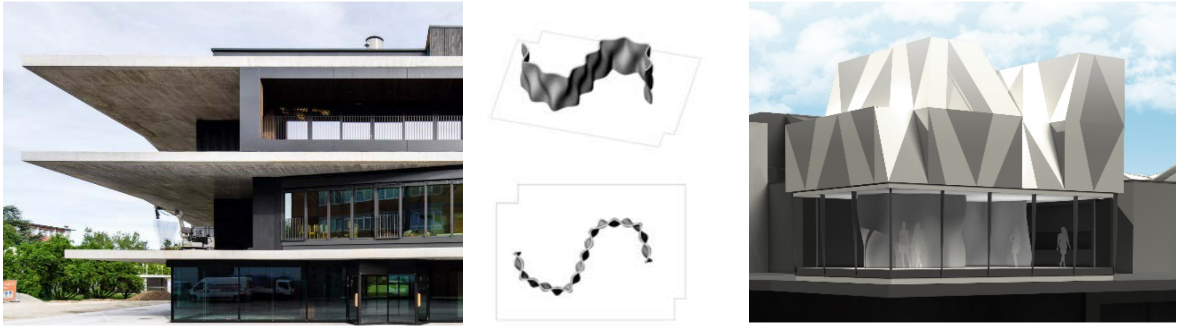
(a) *(b)*

Fig. 7. (a) detail of shear and torsional failure in test MM1_R-NC, (b) test MM1_R-C at peak load

6. STRUCTURAL DESIGN

From a structural design point of view, specific non-standard geometries have a great potential for saving material and leading to lean load bearing structures. For example, double curved geometries can be used to activate membrane resistant mechanisms that are much more efficient than bending resistant mechanisms. Such structurally efficient designs may drastically reduce the amount of reinforcement needed and the concrete section compared to conventional flat designs. Moreover, designers will be free to adapt the mesh orientation according to the structural behaviour for every specific application. Therefore, continuous reinforcement, which has a better performance, could be either placed vertically or horizontally, a flexibility that is provided by the robotic end effector's capability to build meshes in both directions.

For example, we are presently planning a full scale demonstration of Mesh Mould with the on-site fabrication of a double curved wall as part of the Digital Fabrication Demonstrator Unit in the NEST research building at Empa in Dübendorf, Switzerland. The Mesh Mould technology will be used to build a curved wall, acting as the primary loadbearing structure of a three story residential building unit. The surface curvature of this wall will be activated structurally to minimize its cross section while providing lateral stiffness to the building superstructure in horizontal directionand improving the bending behaviour of the wall in vertical direction. A structural analysis currently in progress will determine the optimal mesh orientation in this wall to most efficiently resist the governing loads acting on the overall structure.



(a) *(b)* *(c)*

Fig. 8. (a) Mesh Mould on-site demonstration at NEST, 2016, (b) wall geometry, (c) wall in NEST Unit context

In such structures, a membrane behaviour is expected. In order to achieve a ductile behaviour, the tensile capacity of the reinforcement must be able to resist the cracking load of the concrete and guarantee a strain hardening behaviour after cracking. Considering the mechanical properties of the materials currently used, this means that a geometrical reinforcement ratio (area of reinforcement/concrete area) of approximately 1% is required for the meshes in each direction. This amount exceeds typical standard requirements for walls, as for example the minimum needed to control shrinkage cracking, and will provide adequate robustness of the structure.

For full scale objects as shown in Fig. 8c, the stated ductility requirement in terms of steel content leads to very small mesh cell sizes (below 10 mm) when using Ø3 mm wires. This would lead to very long production times and is the reason why we are upgrading the present robotic end effector to accommodate wires up to Ø6 mm. This factor two change in the diameter implies a factor 4 change in the number of wires and a factor 16 reduction in the number of welding points, which is one of the rate limiting parts of the process. Therefore, substantial speed gains can be expected in additional to the optimization of the robot itself.

Another interesting option is to include fibres in the concrete mix design. By doing so, it would be possible to increase the mesh size and also reduce its production time. This comes however at the expense of a reduced capacity of keeping the material within the mesh. Nevertheless, by using large fibres and properly designing the concrete mix, it should be possible to produce self-compacting mixes easy to cast in the centre of the wall, but exhibiting substantial jamming when trying to flow out laterally. This exemplifies a very direct example of how questions of material design, robotic fabrication and structural design are tightly interlinked and why a strong collaborative effort is needed to produce large scale, load bearing and structurally optimized structures allowing minimization of material use in construction.

7. CONCLUSION & OUTLOOK

The development of the Mesh Mould technology, a robotic fabrication process for non-standard shape reinforced concrete structures, has been documented in this article. Freeform steel wire mesh geometries have been designed and constructed by use of a mobile robot with a specially designed robotic end effector. Thanks to innovative positioning algorithms, this robot can operate either in prefabrication or on site environments. This mesh fabrication process still presents many potentials for optimization that are guided by mechanical considerations and structural design requirements.

These changes however impact another processing step, which directly concerns concrete technology. In essence the question is how to fill the mesh with a self-compacting mix that does not flow out laterally. On this front simple tests have been presented to facilitate the quantification of the mix design factors at stake. They have highlighted a combined role of yield stress and aggregates grading, pointing to an important potential of engineering the blocking capacity of these mixes in relation to the mesh cell size.

To fully enable this technology to produce viable structural systems, adequate reinforcement is essential and presents Mesh Mould with a marked advantage over most other digital fabrication processes being developed today for concrete elements. However, it has been shown that to realize this potential a global optimization process is needed, not only involving considerations from concrete technologists, but also roboticists, structural engineers and architects. In this sense Mesh Mould represents a true interdisciplinary project bearing the corresponding limitations and constraints, but also presenting a fantastic potential for exploiting synergies to achieve performances far beyond what could be expected otherwise.

8. ACKNOWLEDGMENTS

The PhD work of Norman Hack was funded by Sika Technology AG as well as the National Centre for Competence in Research in Digital Fabrication in Architecture from the Swiss National Science Foundation, which funded much of the research contained herein. The authors would also like to thank Andreas Reusser of the ETH Zurich Institute for Building Materials, as well as our technicians Michael Lyrenmann and Philippe Fleischmann for their critical support throughout the project. Finally, the following civil engineering students who carried out their bachelor thesis in relation to mesh filling are warmly thanked: Kaja Wenk, Deniz Yilmaz, and Aline Rieder.

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