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Mesh Mould - A structural stay-in-place formwork system for robotic in situ fabrication of non-standard concrete structures: A real scale architectural demonstrator

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Abstract

Concrete is a highly versatile construction material, not only for the reason that it has excellent properties in terms of structural performance, building physics, availability and price, but also because it can be moulded into virtually any shape regardless of its geometric complexity. However, even though current digital design tools allow to effortlessly design and calculate structures, which are exploiting these properties, this potential remains all too often unrealized. This is due to the fact that geometrically complex concrete structures require expensive, one-of-a kind formwork, which can often not be reused or even recycled. Consequently, the current practice for producing non-standard curvilinear architecture in reinforced concrete is neither ecologically sustainable nor economically feasible for a broader range of architectural typologies. Additive Manufacturing (AM) processes, like 3D printing with concrete, on the other hand, currently struggle with the integration of structural reinforcement, limiting the technique to predominantly compression-loaded applications. This research addresses both issues and proposes Mesh Mould, a robotic fabrication process that unifies concrete formwork and structural reinforcement, and hence potentially reduces formwork waste and construction costs for non-standard reinforced concrete constructions. The development of a fully automated robotic fabrication process involved various research disciplines, including architecture, material science, mechanical engineering, robotics as well as civil engineering. This paper describes the technological developments of the Mesh Mould construction system that were necessary to meet the challenges of 1:1 construction. The results are demonstrated in a final loadbearing structure, the Mesh Mould wall of the DFAB HOUSE on NEST.

1 Introduction

Over the past decade, research in robotic fabrication has opened up entirely new avenues for the design and the materialization of architecture [1]. Whereas researchers have investigated a vast range of material processes [2–4], lately there is an intensified interest in robotic fabrication with concrete [5]. This interest is not least due to concrete`s potential to be cast into virtually any shape, enabling the materialization of geometrically complex and material-efficient loadbearing constructions. Apart from traditional casting techniques, the majority of research today focusses on Additive Manufacturing with concrete [6]. Even though, this technique has made significant advances since its invention two decades ago [7], the automated integration of structural reinforcement today still remains a challenge [8]. In consequence, currently structural reinforcement either needs to be placed post hoc in a labor-intensive manual process, or building elements fabricated with AM technology remain limited to compression-only constructions [9]. Mesh Mould - the robotic fabrication technique presented in this paper addresses these limitations from the perspective of structural reinforcement and brings forward a novel approach for digitally designing and fabricating geometrically complex, fully loadbearing non-standard reinforced concrete constructions.

2 Background and motivation

Among architects and engineers, there is a long-standing desire to express the intrinsic qualities of concrete, being a mouldable construction material. The expressive "béton brut" constructions of Le Corbusier, the elegant curvilinear buildings of Eero Saarinen, or the highly articulated rib structures of Pier Luigi Nervi all represent a formal language, inherent to concrete as a mouldable construction material. Particularly today, as contemporary digital tools are inherently inclined towards curvilinear geometries, the desire to explore and open up new sculptural dimensions in concrete construction further intensified. Buildings such as UNStudio's Mercedes Benz Museum [10, Fig. 1a], the EPFL Rolex Learning Center of SANAA Architects [11, Fig. 1b], or the Taichung Opera House of Toyo Ito & Associates [12, Fig. 1c] have recently demonstrated how advances in design exploration on one hand, and improvements in fabrication technology on the other, have enabled unprecedented formal complexities and structural performance. Nevertheless, the challenge remains to realize such structures in an economically and ecologically feasible way.

(a) (b) (c)

Fig. 1: Contemporary concrete architecture: (a) Mercedes Benz Museum, UNStudio, Stuttgart, 2006; (b) EPFL Rolex Learning Center, SANAA Architects, Lausanne, 2010; (c) Taichung Opera House, Toyo Ito & Associates, Taichung 2016.

The main limiting factors are the high expense of time, labor and material involved in the construction of custom formwork which is required for the realization of geometrically complex concrete constructions. According to [13], already for simple planar geometries, the costs for formwork account for over 50% of the total production cost of a concrete structure. For geometrically more complex constructions, as for example double curved geometries, the costs of the custom formwork can increase to account for up to 75% of the structure's overall production cost [14]. Similar figures have recently been confirmed by [15], who compiled a detailed analysis of the construction costs for straight and double curved concrete walls, using conventional construction techniques. Accordingly, with 430 -720 USD/m^2 the actual costs for a double curved concrete wall is up to eight times higher than for a geometrically simple, straight wall. Furthermore, non-standard curvilinear mould constructions are usually produced as unique elements, which often cannot be reused or recycled [16, Fig. 2]. As a result, through the use of common formwork technology non-standard, curvilinear reinforced concrete structures are economically and ecologically not sustainable today.

(a) (b)

Fig. 2: EPFL Rolex Learning Center construction process: (a) installation of the unique formwork tables; (b) construction waste after stripping the formwork.

An analysis of existing formwork technologies identified a historical concrete construction system, that unifies reinforcement and formwork, and that was found to be particularly well suited for being adapted towards robotic fabrication. This so-called "Ferrocement" technology is based on layers of thin steel wire meshes, which are manually formed and successively covered with a cement mortar [17]. The use of meshes with small wire diameters enables simple forming, while a dense cell spacing facilitates sufficient containment of the concrete. Due to the physical pliability of the wire mesh, the system is generally capable of producing geometrically complex, non-standard geometries.

Initially invented by Joseph-Louis Lambot in 1848 [18], the system was, amidst World war II, rediscovered by the Italian engineer-entrepreneur Pier Luigi Nervi as a materially efficient and structurally highly performative material system. Throughout many physical experiments, Nervi succeeded to develop a construction system that was as "ductile and foldable as metal foil" [19], and which allowed him to eliminate all wooden formwork as well as the constraints associated with it. Later, in his 1945 publication, "Scienza o arte del costruire?" [20], Nervi concluded:

> *"The formwork which represents the real weakness of reinforced concrete from a constructive and economic viewpoint becomes absolutely superfluous. The metal reinforcement made up of netting and bars can adapt with great ease to curved surfaces or any type of skewing. Its intrinsic lightness and deformability mean that it can be supported with light scaffolding, which enormously simplifies the construction of large and very large roofs."*

Nervi patented the system [21], and subsequently renamed it to "Ferro-cementitious Felt", an analogy carefully chosen to reflect the density of the metal meshes, and moreover the traditional technique of hat making – an example that Nervi often used to illustrate the concept of "strength through form" [19]. The first time Nervi applied this technology to civil construction was for erecting the material storage of his own Firm "Nervi & Batoli" in Via Magliana in Rome [22, Fig. 3a and 3b]. The 21.88 x 11.38 m wide shed and its many undulations and folds for stiffening became a hallmark building for Nervi's quest to find an appropriate formal expression for the use of this construction system.

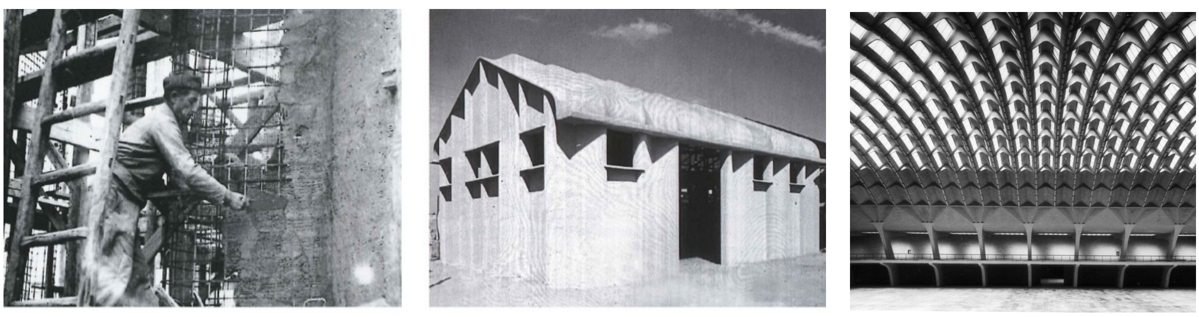


Fig. 3: Ferrocement buildings: (a) manual application of cement mortar; (b) finished building, Pier Luigi Nervi, Rome, 1945; (c) exhibition hall for the Turin moto show, Pier Luigi Nervi, Turin, 1948.

After further investigations, Nervi managed to scale up the process and apply the technique to the construction of the famous corrugated roof structure for the exhibition hall in Turin, erected between 1948 and 1949 [22, Fig. 3c]. Nervi was certain that the invention of the Ferro-cementitious Felt would lead into a new era of designing and constructing with reinforced concrete. One drawback however, which Nervi had not fully considered at that time, was the high amount of manual labor involved in the fabrication and installation of the exceedingly articulated elements on site. Eventually, the rapidly increasing labour costs in post-war Italy rendered this “artisanal” construction system economically unfeasible [19], and thus did not have the lasting impact on architecture that Nervi had initially envisioned. The research project presented here is based on the assumption that construction techniques, similar to Nervi`s Ferro-cementitious Felt, can be economically revived through the use of digital manufacturing technology. Accordingly, with reference to Nervi’s Ferrocement technology, the Mesh Mould research focused on the exploration and the development of a digital design and robotic fabrication process for non-standard loadbearing concrete structures. In contrast to most other digital concrete construction approaches, here the research focused on making structural reinforcement an integral part of the fabrication process. This integration is accomplished by unifying reinforcement and formwork into one robotically controlled fabrication process. In more detail, the concept works as follows: A mobile 6-axis industrial robot, equipped with a custom developed end effector, automatically fabricates a dense three-dimensional reinforcement mesh directly on the construction site [23]

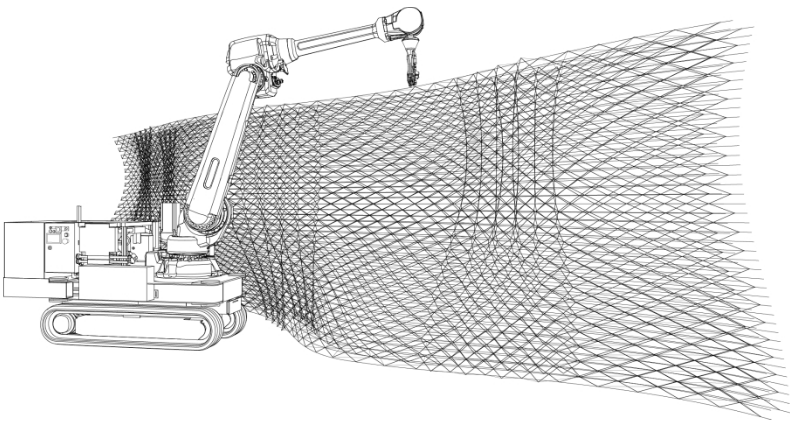


Fig. 4: Concept diagram of mobile 6-Axis robot fabricating a three-dimensional mesh.

After fabrication, the mesh is filled with concrete, which slightly extrudes through the mesh surface. This excess material is manually trowelled in order to create a smooth concrete surface finish. The form-giving mesh remains inside the concrete structure, acting as reinforcement [23]. By means of unifying formwork and reinforcement, the goals pursued in this research were: first, to provide loadbearing capacities in both directions, compression and tension, and thus making digital concrete construction applicable to real-world building processes and applications. Second, to eliminate construction waste, which is usually caused during the production and the disposal of one-of-a-kind formwork. Third, to extend the freedom of design through the employment of a digitally controlled robot. Fourth, to realize Nervi’s concept of “strength through form”, by using geometric complexity to increase structural performance. And last, the long-term goal, to reduce the excessive costs associated with concrete formwork, and to make non-standard geometries applicable to wider range of building tasks.

Whereas preliminary conceptual phase of this research focused on the prototypical fabrication of topologically highly differentiated meshes using a custom developed spatial extrusion technique [24], this phase of the research focused on translation of the principles into a structural, stay in place formwork system, in which the mesh is used as reinforcement after the concrete has cured.

3 State of the Art

Regarding the unification of formwork and reinforcement, Formatech [25], a particular type of stay-in-place formwork for walls, had initially inspired the Mesh Mould research. Formatech combines conventional steel reinforcement with a system of corrugated, perforated plastic formwork cages. These cages, with standardized dimensions of 40 x 60 x 20 cm and perforations of 1.5 cm of diameter, contain slots and fixtures for the integration of conventional horizontal and vertical steel reinforcement. After a layer of cages is manually assembled on site, a horizontal reinforcement bar is inserted. Vertical reinforcement is added after several layers of cages are installed. Once the entire structure is erected, a special concrete mix is pumped into the formwork, either from above or frontally. The concrete extrudes through the formwork and covers up its surface. A successive manual trowelling process creates a smooth concrete surface [25, Fig. 5a]. Using the standard Formatech formwork cage system, straight and single curved walls with a constant thickness can be created. Other shapes are generally possible, but would require the production of customized cage geometries. Although, the construction system combines formwork and reinforcement, the functionalities of the form-defining plastic panel and the conventional reinforcement remain largely separated. The Formatech systems is most efficient when used for simple and repetitive geometries. Even though customized geometries are achievable, these create additional costs as individual modifications of the overall system are required.

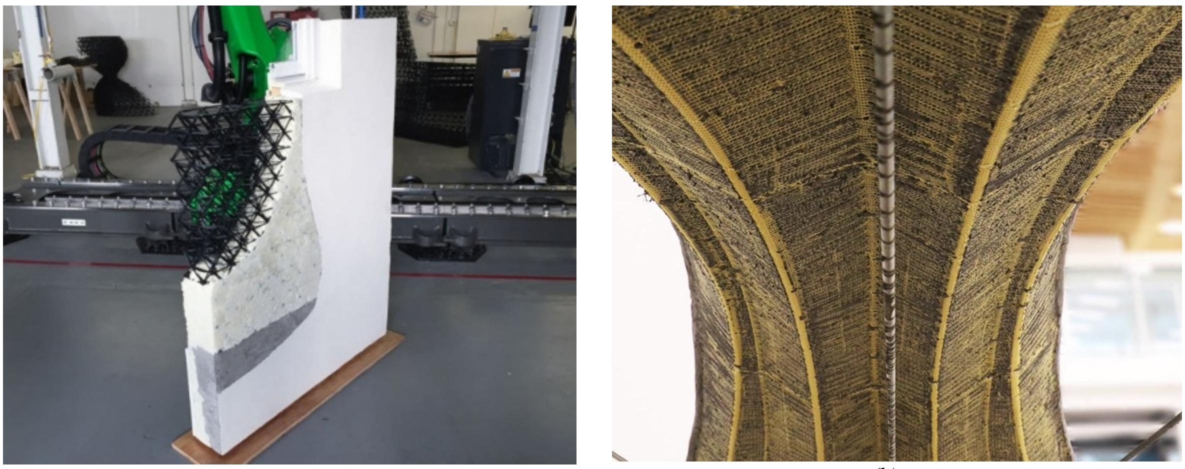
Coffra Suisse [26] developed a structural stay-in-place formwork approach, which serves as a prime example for a unified formwork and reinforcement system. The company developed the so-called "3DR" reinforcement cage system, which consists of CNC bent, and subsequently manually assembled, multi-layer steel reinforcement elements. The assembled cages are covered by a stainless-steel rib lath, acting as a permeable membrane facilitating the containment of concrete during filling. This permeable, metal surface moreover allows for a self-regulated release of the concert's excess water, reducing the hydrostatic pressure within the cage of up to 80 %. According to the manufacturer, this allows filling heights of up to 12 meters in a single pour, without the necessity of heavy support structures. A typical filling procedure is depicted in Fig. 5b. The combination of CNC pre-fabrication and manual assembly makes the system geometrically versatile and allows for diverse geometries ranging from straight to single curved typologies. Various structural elements can be realized, including beams, columns, slabs as well as flat or inclined roofs. After infill and curing of the concrete, the rough concrete surface is covered with conventional plaster or other surface constructions, for example wooden panels. The versatility and the applicability of the construction system was demonstrated in numerous large-scale projects, including the Centre de Congrès de Mons by Studio Daniel Libeskind, [29, 30].

(a) *(b)*

Fig. 5: Manually assembled stay-in-place formwork technologies: (a) Formatech`s perforated plastic cages;(b) Coffra Suisse 3DR cages.

In contrast to manual assembly processes, the use of digital fabrication technology enables the production of stay-in-place formwork systems with significantly higher geometric design freedom. Following this approach, in 2015 the US-based start-up Branch Technology, launched the so called "Cellular Fabrication" technique, a spatial printing process for freeform stay-in-place formwork. The fabrication setup comprises of a 6-axis industrial manipulator, equipped with a customized end effector for spatial printing with Acrylonitrile Butadiene Styrene (ABS) in diameters of up to 4 mm [29].

Whereas the fabrication technique is largely identical to the pre-steel Mesh Mould approach [23], the start-up uses a slightly different filling strategy. Instead of filling the mesh uniformly with concrete, the company proposes a multi-material filling approach. Accordingly, the wall system consists of a spatially extruded polymer mesh, a layer of construction foam, concrete and plaster. This filling strategy was presented in several mid-size concept prototypes [32, Fig. 6a].



(a) *(b)*

Fig. 6: Digital stay-in-place formwork technologies: (a) Cellular Fabrication by Branch Technology; (b) Knitcrete by Block Research Group

Another highly digitized approach for semi-integrated stay-in-place formwork system is the KnitCrete research project by Block Research Group at ETH Zurich [31]. KnitCrete introduces an innovative approach for the fabrication of geometrically complex, anticlastic shell geometries that allows to reduce material and labour costs. The system comprises three components: Firstly, an automatically knitted three-dimensional technical textile acting as formwork; secondly a steel cable net functioning as reinforcement; and thirdly an external framework for tensioning the cable net and the formwork textile. Due to the sophisticated design to fabrication workflow, additional geometric functionalities like for example the guides and ducts for the reinforcing cable net, or cavities for the integration of displacement bodies can be automatically generated and fabricated in an integrative manner. In a collaboration between Block Research Group, the Chair of Physical Chemistry of Building Materials of ETH Zurich and Zaha Hadid Architects' Computational Design Group (ZHCODE) KintCret`s design potentials and structural capabilities have recently been demonstrated in the KnitCandela project at the Museo Universitario Arte Contemporáneo in Mexico City [32].

The review of the state-of-the-art demonstrated that industrial applications for stay-in-place formwork systems, like Coffra Suisse, have not yet tapped into the full potential of digital fabrication, as still a large degree of manual labour is involved in the assembly process. In turn, the more digitized fabrication processes, as for example pursued by Branch Technology, are not yet meeting the structural requirements of real-world construction and industrial applications. In conclusion, the review of the state-of-the-art has identified a large potential regarding the formal, structural, economic and ecological capacities of a fully integrated design and fabrication process for structural stay-in-place formwork systems.

4 Method

(a) *(b)*

Fig. 7: Empa NEST: (a) Gramazio Kohler Architects, Dübendorf, 2016; (b) Rendering of the DFAB HOUSE at Empa NEST.

DFAB HOUSE on NEST: The newly inaugurated modular research and innovation building NEST [35, Fig. 7a] of the Swiss Federal Laboratories for Materials Science and Technology (Empa) provided the unique opportunity to collaboratively realize a fully functional, real-world building demonstrator, the so-called DFAB HOUSE [36, Fig. 7b]. The DFAB HOUSE, which builds upon a series of innovative digital construction technologies was developed within the NCCR Digital Fabrication research platform [35]. The housing unit is conceived as a three-story building, consisting of five different construction innovations (Fig. 8): starting from top, a two-story robotically assembled modularized timber construction [36] that features a lightweight translucent aerogel façade, a post-tensioned concrete slab (Smart Slab) fabricated with a 3D printed sand formwork [37], fifteen robotically slip-casted concrete façade mullions [38], and finally, the fully loadbearing Mesh Mould wall [39] fabricated by a mobile construction robot, the so-called In situ Fabricator [40].

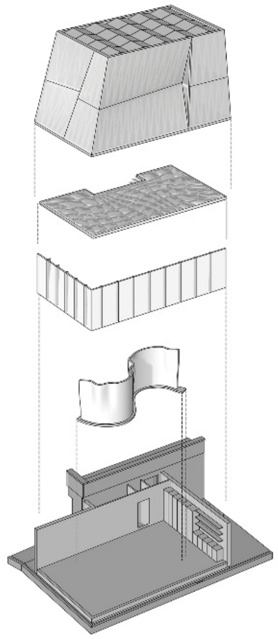


Fig. 8: Explosion drawing of the DFAB HOUSE showing the Innovation Objects.

The Mesh Mould wall was designed as a space defining, twelve-meter-long, undulating and fully loadbearing architectural element, carrying approximately 86 tons of design loads from the structures above. The research challenges regarding this real-world implementation of the Mesh Mould system were manifold. They included, for example investigations into suitable mesh typologies, the development of a specialized robotic end effector, the development of a computational design and fabrication workflow, the elaboration of advanced concrete recipes and filling techniques, as well as structural investigations validating the loadbearing capacity of the wall. Facing those challenges, various interdisciplinary collaborations within the NCCR Digital Fabrication were established, integrating the disciplines of architecture, material science, mechanical engineering, robotics as well as civil engineering. The following paragraphs describe the key technological innovations, which were necessary in order to face the challenge of a real-world construction project.

Mesh typology: The initial challenge was to develop a fabrication informed steel mesh typology that satisfies a number of multidisciplinary and partially conflicting constraints. For example, the mesh needed to be able to retain fresh concrete, allow for rapid and collision-free fabrication, and be sufficiently strong to act as reinforcement after the concrete has cured. For this, a cell size of approximately 40 x 40 mm was found to be a local optimum, considering competing parameters as for example fabrication speed, machineability and mesh permeability. In accordance with the structural requirements, and taking into account the optimal cell size, the slenderness of the wall and the bending stress, the use of 4.5 to 6 mm B500B reinforcement steel was specified. The mesh typology, developed according to these constraints, consists of a polygonalized continuous steel rebar, which is orthogonally crossed and connected by discrete welded reinforcement elements.

The process steps involved in the fabrication of the three-dimensional steel mesh typology comprised of wire feeding, wire bending, cutting and welding. A particular challenge was to find a welding method that could weld the steel bars rapidly and structurally. For this purpose, the cross-wire welding process was chosen, the main feature of which is that two crossing rebars are melted at their point of contact by a high current and are immediately structurally by pressing them together.

Manipulator and robotic end effector: Based on the mesh typology described above, two iterations of a robotic end effector were developed. A first version, which processed steel wires of smaller diameters up to two millimetres is described elsewhere [41]. Both versions of the end effector incorporate six degrees of freedom, which, in addition to the six degrees of freedom of the industrial manipulator, was determined the minimum number required to fabricate double curved meshes. The fabrication routine includes two scales of manipulation; firstly, the local manipulation of the steel wire performed by the end effector; and secondly, the global positioning of the end effector, performed by the robot arm. For the latter, the robot orients the end effector and moves it from point to point, whereas the local routine, executed by the end effector itself, consists of bending, feeding, cutting and welding the steel rebar. Local manipulation is distributed on two parts of the end effector: the front part and the rear part. The front part contains the bending function for the continuous horizontal rebar, whereas the rear part holds all technical components for clamping, feeding, cutting and welding. A 3D model of the end effector with the functional components is depicted in Fig. 9.

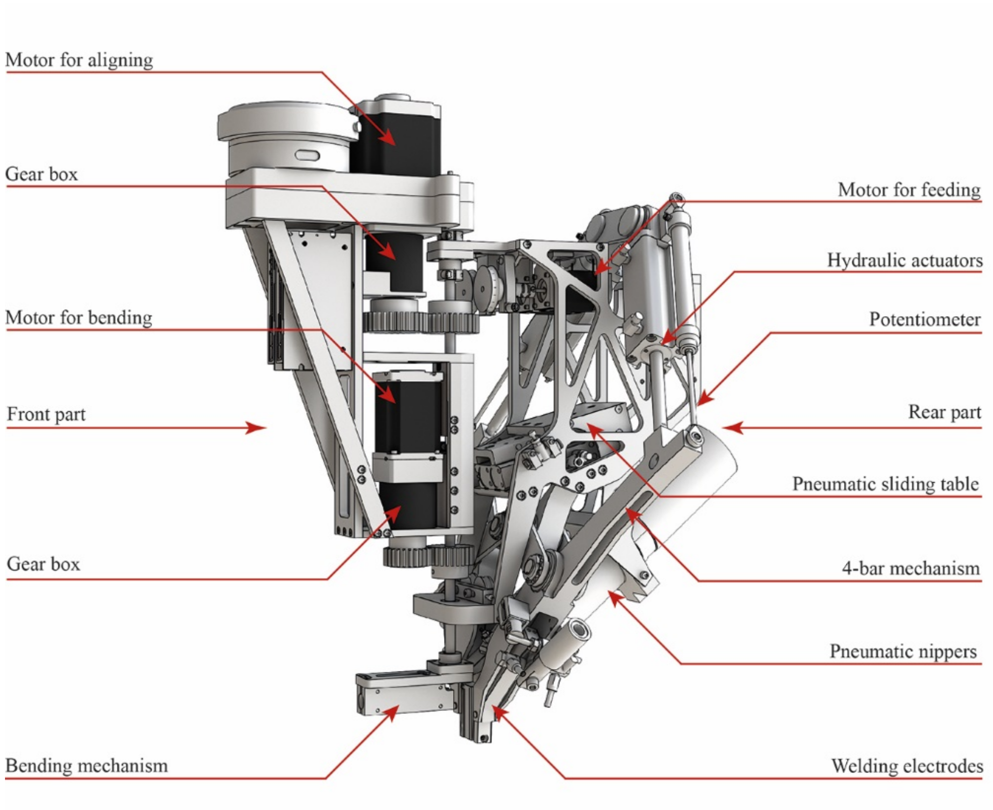
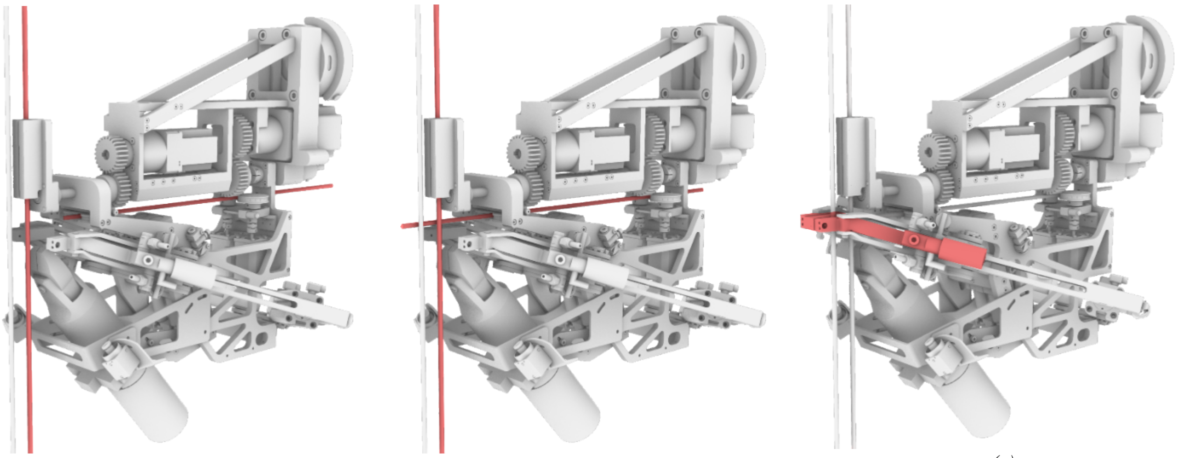


Fig. 9: End effector and its main technical components.

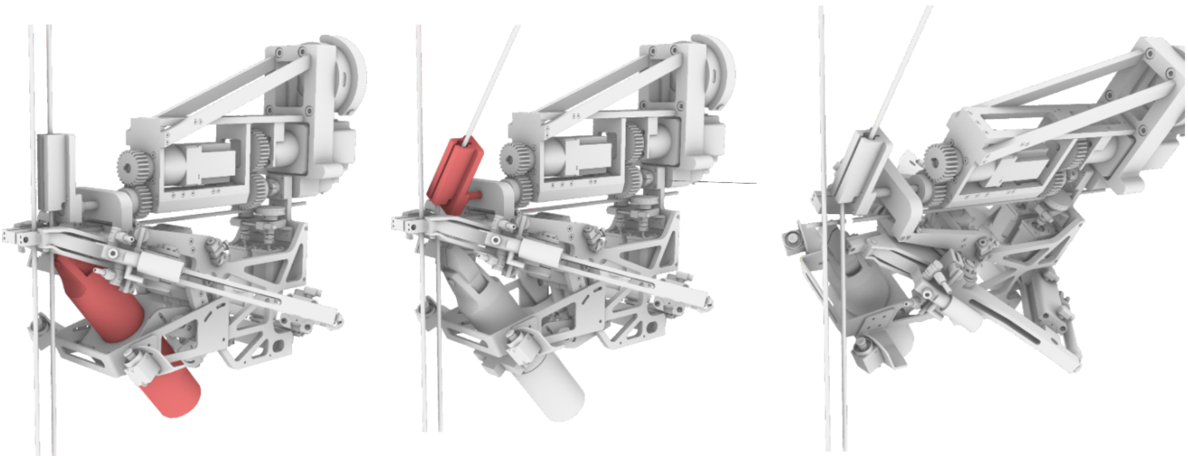
Fig. 10 and Fig. 11 show the fabrication sequences involved in the production of a mesh, whereas each sub-step marked in red. First, a 6 mm steel bar is inserted into the vertical, and a 4.5 mm bar into the horizontal guiding mechanism of the end effector (Fig. 10a). Once the robot positioned the end effector in the correct three-dimensional position, the horizontal wire is fed forward via the feed rollers until it crosses the lower and upper reinforcement bar (Fig. 10b). Next, the 4-bar mechanism is activated, the welding electrodes close and the reinforcement bars are clamped (Fig. 10c).



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

Fig. 10: Fabrication sequence part I:(a) initial state; (b) feeding of the horizontal wire; (c) closing of the welding electrodes.

This is followed by the cutting cycle. For this, the pneumatic sliding table is activated and the nippers are rapidly guided towards the reinforcement bar. After the nippers have been activated and the rebar was cut, the nippers slide back to their initial position to avoid collisions during the following steps (Fig. 11a). Subsequently, the resistance welding signal is triggered and the rebars are connected. The bending mechanism is then activated and the vertical wire is bent (Fig. 11b). Finally, the electrodes open, the rear part of the end-effector aligns with the front part and the end effector moves to the next position where the procedure is repeated (Fig. 11c).



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

Fig. 11: Fabrication sequence part II:(a) cutting of the horizontal wire; (b) bending of the vertical wire; (c) realigning of the end effector.

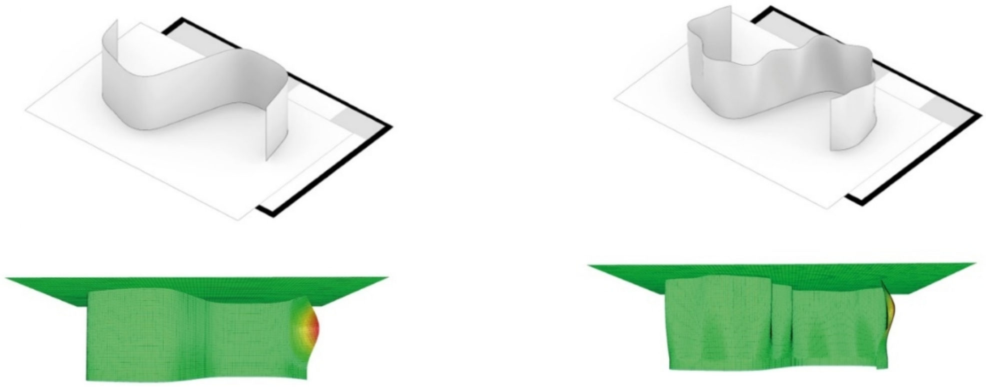
For global positioning, the end effector was attached to the mobile robotic fabrication platform, the so-called In situ Fabricator (IF). IF consists of an ABB IRB 4600 industrial robot, mounted on a custom mobile platform, which is driven by hydraulic caterpillar tracks. The electrically powered mobile robot carries all necessary equipment for autonomous on-site fabrication on board. As such, IF contains an industrial controller, a battery pack, an on board computing system and various sensing units for on-site localization [42]. The robotic setup has a maximum payload capacity of 40 kg, a self-weight of approximately 1400 kg and a spherical stationary reach of 2.55 m. Due to its capacity to change position however, this reach is virtually extended infinitely in xy world coordinates.

Parametric design tool: In order to avoid the need for post-rationalization of the design, as is often the case in conventional design processes, the main fabrication constraints of the fabrication process were integrated directly into the Mesh Mould design workflow. This integrated approach constrained the design space exclusively to buildable solutions. Already in the early design phase, it was decided to exploit the geometric freedom offered by this robotic fabrication process, and to increase the stiffness of the wall through double curvature. For this, a parametric design tool was specifically developed to design walls locally containing regions of double curvature. A planar input curve drawn by the user serves as a basis for the generation of an initial NURBS surface. Subsequently, the amplitude, frequency and phase modulation of the geometry can be parametrically modified to define the local undulations of the wall (see Fig. 12a). Once settled for a specific design option, the mesh typology is automatically generated while simultaneously checking for fabrication constraints. For that matter, the algorithm highlights geometrically predictable collisions between the robotic end effector and the mesh, as well as it indicates cells that are geometrically exceeding the given fabrication constraints (see Fig. 12b). Following this analysis, the geometry can be parametrically adjusted until all fabrication related conflicts are resolved. Lastly, the final mesh geometry is generated (see Fig. 12c).

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

Fig. 12: Computational design tool: (a) parametrically modifiable surface; (b) indication of anticipated fabrication conflicts; (c) generation of the mesh geometry.

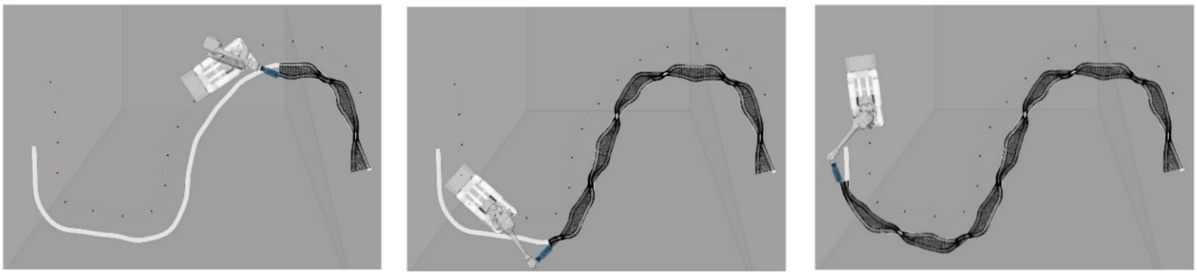
Design evaluation: While architectural design is often a matter of subjective judgement, there are also quantifiable, functional parameters that can be used when choosing one design option over another. This becomes particularly valuable, for example, when using parametric tools for the generation of geometry as those tools enable the designer to generate endless variations of one object [43]. For the DFAB HOUSE wall, a computational evaluation procedure was established to automatically compute a linear elastic Finite Element (FE) analysis of the different design geometries. The Compas framework [31] linked the design geometries to the FE-analysis software Abacus [44] and parsed the results into the Rhino 3D CAD-environment. This workflow allowed a preliminary comparison of the structural performance. Already in the early concept phase, the intentional use of the double curvature was used as a design parameter to control the structural performance of the wall. In this respect, the example in Fig. 13 illustrates, that local use of the double curvature can double the buckling resistance compared to a single curved wall.



(a) *(b)*

Fig. 13: Comparative structural evaluation, (a) single curved design surface and buckling behaviour analysis resulting in a factor of 255; (c) undulated, double curved design surface and buckling behaviour analysis resulting in a factor 489.

On-site building strategies: The exploration of key design parameters, such as shape based structural performance and geometric end effector constraints, was furthermore supplemented by the investigation into the fabrication constraints deriving from building with a mobile robot system [45]. In particular, the aim here was to streamline the fabrication process in a way that the reach of the robotic arm can be optimally utilized, and that the time-consuming repositioning and referencing of the robot can be reduced. In the previous experiments the mesh was fabricated in a horizontal orientation, where horizontal layers were stacked on top of each other in order to fabricate the object [46]. While this assembly strategy is well suited for the prefabrication of wall segments, for which the robot does not have to be repositioned, it is impractical for the in situ fabrication of larger continuous structures. In the case of the 12-meter-long Mesh Mould wall, a horizontal build-up strategy would imply that the robot must move along the entire length of the wall for each horizontal layer. Apart from the issues of handling very long reinforcement bars, this would also involve the robot having to be repositioned and referenced prohibitively often. Hence, an alternative, vertical build up strategy was developed. In this 90° rotated, vertical fabrication strategy, the robot fabricates each layer from bottom to top. Accordingly, the final wall is composed of vertical layers lined up one after the other. The advantage of this strategy is that batches of about 1.5 m in length can be fabricated to full height before the robot has to be repositioned. (Fig. 14 and Fig. 15). Adding to this, a vertical orientation of the continuous reinforcement was likewise considered the favourable direction in terms of structural design.



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

Fig. 14: Building in vertical batches: (a) after four repositioning routines; (b) after eight repositioning routines; (c) after twelve repositioning routines.

Adaptive fabrication strategies: In order for the robot to refererence its position on site and to detect inacuracies during fabrication, advanced sensory capabilities were necessary. For this, two complementary vision-sensing systems were developed for in situ fabrication. First, a global localization system for precise and fast robot localization after repositioning and second, a local mesh registration system in order to compensate for inaccuracies caused for example by the steel's spring back behaviour. Introducing the global state estimation system, the goal was to enable the robot to localize its own base position in relation to its surrounding environment. The base localization system consists of two components: first, fiducial markers, which are equally distributed and rigidly mounted on a precisely measured substructure of the wall, and second, a camera system, which is implemented at the robot's end effector (Fig. 15).

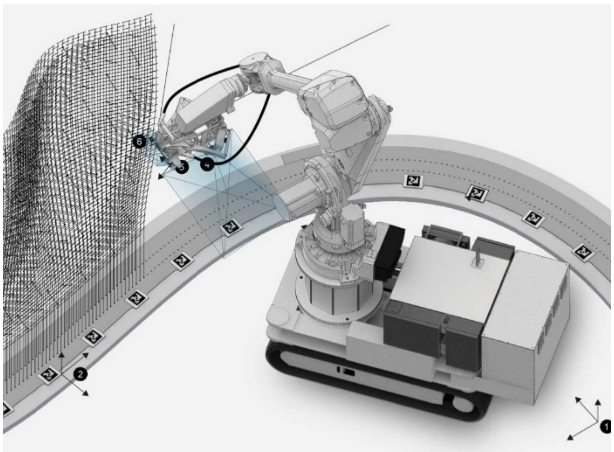


Fig. 15: Camera system for local and global state estimation

In an initial calibration step, all tags were recorded, and were subsequently virtually aligned with the world frame of the CAD model. After each robot reposition, four tag measurements in the proximity of the base were taken, and the robot's new location was calculated. The system was initially designed to deliver an accuracy with deviations below 1 cm and 0.2° in order to ensure smooth attachment to the previously built segment without visible discontinuities. The local state estimation was developed in order to detect inaccuracies in the building process and to incrementally correct them by adjusting the building plan. A stereo vision system, consisting of two additional cameras, also mounted on the tool head, was used to measure the 3d position of all of the welding nodes on a single layer, and compare their location with the CAD model of the mesh. Any calculated differences between as-built and as-planned data is subsequently corrected by adjusting the insertion angle of the discrete steel elements for the successive layers [45]. For reasons of fabrication speed, only every tenth layer-pair was scanned, and the correction angles were successively distributed over the sequence of the next ten layers. More technical details on both, the local and the global estimation, are described in [47].

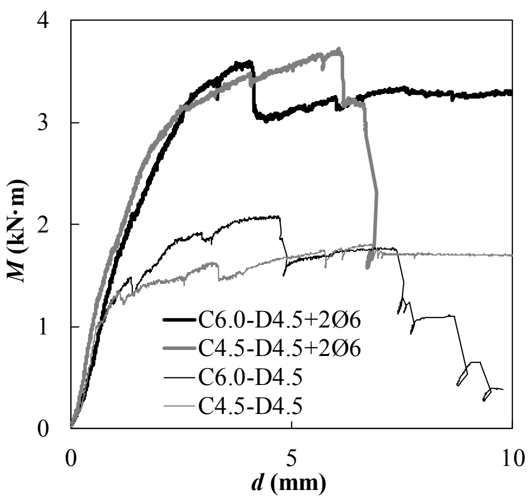
Material: In terms of concrete mix design, two strategies were investigated in parallel: Firstly, the use of a commercially available pre-mix high yield stress mortar [48], and secondly a custom designed mix, which was based on the concept of jamming [49]. The particularity of the latter is the fulfilment of seemingly contradictory requirements. On the one hand the concrete should not to run out of the mesh, on the other hand it is supposed to spread evenly inside the mesh in order to prevent nests or cavities. This was achieved by using approximately 8 cm long polypropylene fibres and recycled crushed brick aggregates up to a size of 4 cm in combination with a self-compacting matrix. The fibres and aggregates are intended to block the mesh openings and prevent the fine matrix from leaking out while the matrix can evenly spread inside the mesh. Regarding the construction workflow, one disadvantage of this mix design is that it is not pumpable and can only be poured into the mesh from above for example by using a concrete bucket. In the comparison, this is a significant advantage of the second mix, which can be pressed through the mesh openings using a conventional concrete pump. Additional reasons to choose the premix over the customs designed mix for filling the Mesh Mould wall were its existing fire and compression strength certifications.

Structure: The reinforcement in Mesh Mould structures is composed of continuous reinforcing bars in one direction, and short welded reinforcing bars in the orthogonal direction. The structural behaviour in the direction with continuous reinforcing bars has been proven to be the same as in conventional concrete structures. The only remarkable difference is that the load transfer between the welded reinforcing bars might generate shear stresses in the continuous reinforcement. Therefore, these shear stresses should be added to the standard actions in the continuous reinforcement. The structural behaviour in the direction of the short, welded reinforcing bars is significantly different from conventional concrete structures. To analyse this behaviour, a series of four-point bending tests was carried out on conventionally cast elements with 400 mm span, 210 mm width and 80 mm depth. The test setup consisted of a length with constant bending of 200 mm. Four reinforcement configurations (Fig. 16) were tested.

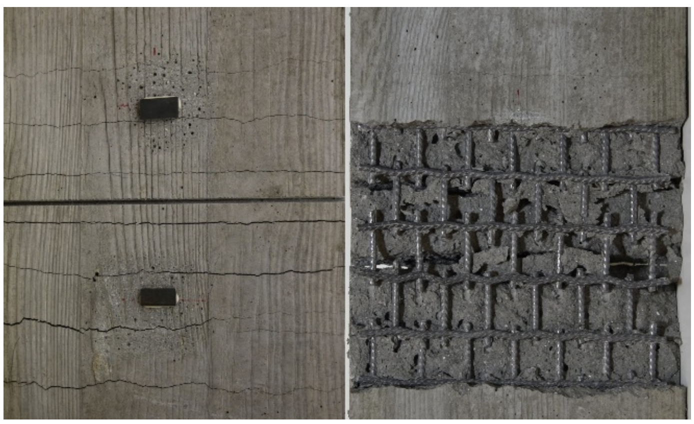
(a) *(b)* *(c)* *(d)*

Fig. 16: Reinforcement configurations for structural bending tests: (a) C4.5-D4.5+2Ø6, 4.5 mm mesh with two additional 6 mm bars; (b) C4.5-D4.5, 4.5 mm mesh; (c) C6.0-D4.5, mesh with 6 mm and 4.5 mm bars in continuous and discontinuous directions; (d) C6.0-D4.5+2Ø6: mesh with 6 mm and 4.5 mm bars in continuous and discontinuous directions with two additional 6 mm bars.

All tests contained the same welded reinforcing bars (reinforcement ratio of 0.6%). The testing parameters were firstly, the diameter of the transversal continuous reinforcement and secondly, the supplementary use of two 6mm bars additionally strengthening the welded reinforcing bars. While the failure mode was rupture of the welding in all cases, the failure was always very ductile (Fig. 17a). This structural behaviour is desirable as it allows for using plastic design procedures also in this direction of the discontinuous welded reinforcement. It should be noted that the ductility, which in conventional concrete structures is provided by yielding of the reinforcement, was given in this case by shear deformations induced in the transversal continuous reinforcement. These shear deformations induced a very particular distributed cracking (as can be seen in Fig. 17b). No differences in the load bearing capacity were observed due to the different analysed diameters for the transversal continuous reinforcement.



(a)



(b)

Fig. 17: Results of 4-point bending structural tests: (a) bending moment-deflection and (b) detail of distributed bending cracks in specimen C4.5-D4.5 (with and without concrete cover).

On the other hand, the strategy of strengthening the meshes with additional reinforcement bars is very efficient and increased by two-fold the capacity of the members. This is a suitable strategy to reinforce local areas with high demanding structural requirements, which was used in the DFAB HOUSE demonstrator, as will be discussed at a later point in this paper.

Computational design: The objective for the design of the Mesh Mould wall was to demonstrate the capabilities of the integrated design and fabrication workflow to generate design solutions with an extended structural and architectural performance. As such, the global s-shape geometry of the wall was determined equally by the structural concept as well as the architectural layout. Hence, the wall organizes the space into different functional areas and provides structural support for all vertical and lateral loads. Variations of the global s-shape can unfold within dedicated zones, which are defined for example by the maximum cantilevering distance of the Smart Slab above, a minimum zone for passageway, as well as predefined functional zones (see Fig.18).

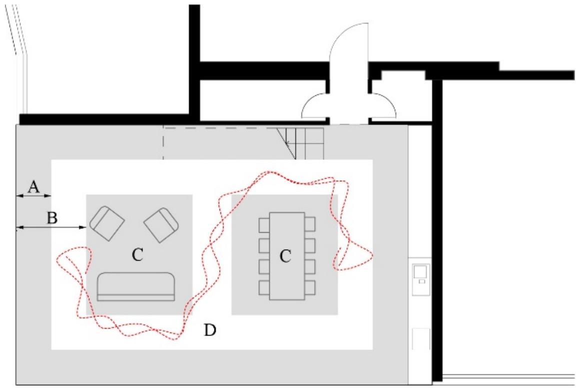


Fig.18: Functional zones of the DFAB HOUSE with two design options: zone A: minimum allowable passageway of 1 m; distance B: maximum allowable span for the cantilevering ceiling of 2 m; zone C: functional zones for furniture; zone D: area in which the wall can develop.

The local differentiation of the wall was particularly influenced by the load case and the structural behaviour of the Smart Slab, resting on top of the wall. Multiple design options were parametrically explored in correspondence to the two structural scenarios: firstly, the celling's structural ribs are crossing the wall perpendicular, creating point loads and secondly, the ceiling rests on an s-shaped beam that follows the wall's top contour curve, creating a linear load. Design solution for both structural scenarios were developed accordingly (see Fig. 19).

(a) (b)

Fig. 19: Design examples for different structural scenarios: (a) local thickening of the wall as a reaction to concentrated loads; (b) local undulations as a reaction to linear loads.

The wall can react to point loads by thickening, while line loads can also be absorbed by geometric folding or undulations. Whereas the former strategy, namely to use more material in places with higher loads, is a common strategy in construction, the latter strategy corresponds to Nervi's concept of "strength through form”. This concept was applied in many of Pier Luigi Nervi’s Ferrocement constructions, as for example the material storage in Via Magliana described earlier [22]. In order to demonstrate the systems capabilities to gain “strength through form” rather than simply adding more material, the linear load scenario in which the vertical forces from above are introduced as linear loads was favoured over a more localized point load scenario. As such, the Smart Slab was designed to distribute the applied loads in the 12 cm thick Mesh Mould wall. As a consequence, the final design of the wall introduces double curvature especially in those areas with higher load concentrations, namely in the middle, and at both ends (see Fig. 20).

Fig. 20: 1:10 model of the final design: the ceiling rests on a linear beam, following the upper contour of the wall.

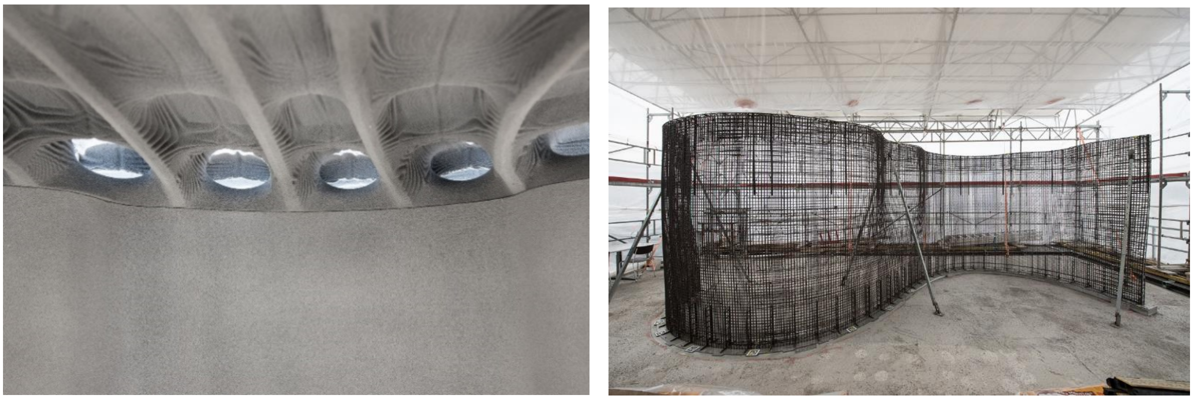
Site preparation: Prior to fabricating the final design on site, several site preparations were necessary. For example, the In situ Fabricator (IF) and the robotic end effector were, in their prototypical stage, not waterproof. Therefore, a weather protecting construction tent was installed on NEST, covering the entire DFAB HOUSE building site. Moreover, a 6.0 mm steel substructure consisting of a vertical starter plate and a horizontal base plate, following the shape of the wall, was installed on site. The base plate contained 6.0 mm holes for the precise placement and manual welding of the vertical reinforcement, as well as sockets with holes for rigidly mounting the fiducial markers. The entire fabrication setup consisted of the In situ Fabricator, the custom robotic end effector, a hydraulic and a pneumatic pump, the welding periphery and the water cooling system. This equipment was stored in a 2.0 x 2.0 x 2.0 m freight container. Together with the pre-straightened 3-meter-long steel rebar of 6.0 mm and 4.5 mm diameter, as well as additional construction site equipment, the container was transported with a crane truck to the site, and successively lifted on the top floor of the NEST building.

Mesh fabrication: After the robot and the technical periphery was installed on site, the fabrication data for the mesh was generated. Subsequently the robot was maneuvered to the first position and fabrication started with moving the end effector to the starting position. Successively, a 6.0 mm vertical and a 4.5 mm horizontal reinforcing steel bar were fed manually into the tool. Through automated bending, cutting and welding, the first layer was fabricated from bottom to top. After welding the last node, the end effector detached from the mesh by automatically moving to a safety plane above the mesh. From this position the tool head moved back to its starting position on the left layer of the same layer-pair (one layer-pair consists of the left and the right layer). New reinforcing bars were loaded for both directions, and the procedure was repeated for the next four layer-pairs. After five layer-pairs, twelve pre-bend hooks, connecting the two parallel mesh surfaces, were inserted in predefined locations and fixed by manual welding. Fabrication continued for another batch of five layer-pairs. After having built ten layer-pairs, the last layer was scanned and the next fabrication sequence was updated. Subsequently, the entire routine was repeated for 6 to 8 batches, until the previously simulated reach limitations of the robotic arm required the mobile base to reposition. The building progress is depicted in Fig. 21, a video of the process is available in [50].

(a) (b) (c)

Fig. 21:Fabrication progress on site: (a) 5.4 m built on day ten; (b) 7.2 m built on day sixteen; (c) 8.5 m built on day seventeen.

Post-reinforcing: In order to meet all building code requirements, a small amount of reinforcement was installed manually after producing the mesh. This included twelve 1-meter-long, 20 mm thick, vertical compression reinforcement bars in order to anchor the Smart Slab in the locations where the ribs cross the wall (Fig. 22). Additionally, open stirrups on top of the wall as well as on both ends were installed for reinforcing the edges. According to the four-point bending tests in described earlier, the mesh was locally reinforced in the horizontal direction. These additional bars were only required in the upper und the lower regions of the wall of the wall, as well as in the area with the biggest curvature.



(a) *(b)*

Fig. 22: Structural adaptations: (a) Model close-up of the ribs crossing the wall; (b) Final mesh including the additional reinforcement including the compression reinforcement below the crossing points.

Filling: Regarding the concreting process, a premixed Sika Monotop 412N [48] high strength mortar was used. The workflow for filling contains the following steps: the material was pumped frontally into the mesh, while one worker was minimizing material loss by holding a plastering float from the backside against the mesh. In areas where voids occurred, the material was consolidated by creating vibrations through knocking on the mesh with the trowel's grip. Approximately five minutes after the material was pumped inside the mesh, the material was smoothed using a trowel. The filling process is depicted in Fig. 23.

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

Fig. 23: Filling process: (a) trowelling the freshly filled mesh; (b) close-up of the filling process showing the un-trowelled concrete; (c) filling the upper region of the mesh.

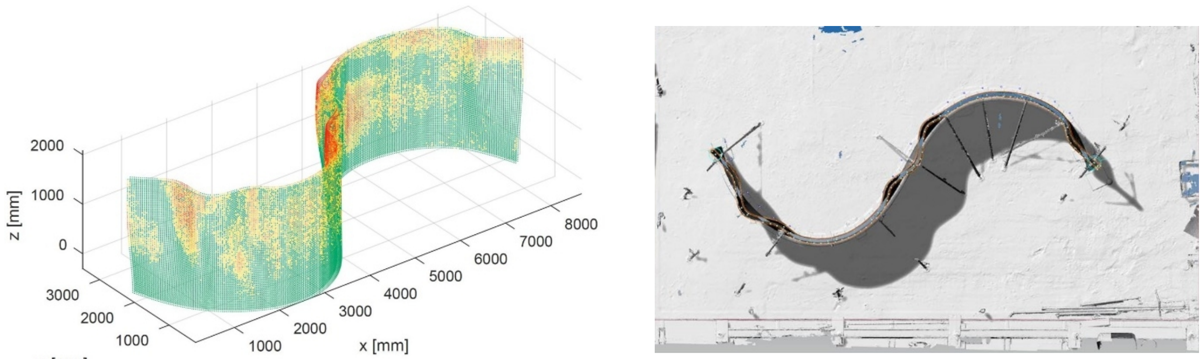
Surface finishing: For the surface finish a finer Sika Monotop 352N [51] was applied using a mortar pump and a spray nozzle. The shotcrete was applied from a distance of approximately 50 cm, using a PFT Swing L mortar pump [52] and a wet spray nozzle. Segments of approximately 2 m of width were sprayed in horizontal layers from bottom to top (Fig. 24a). Shotcreting one side of the wall, equalling 36 m^2, took approximately 15 min. After the concrete had initially cured for 30 min, the surface was trowelled with a customized trowel, containing steel rollers with a radius of 2 cm in order to ensure a consistent concrete cover thickness (Fig. 24b). After letting the surface cover cure for another two hours, the surplus material as well as surface bumps were evenly scraped off with the edge of the trowel creating a smooth, velvet-like texture (Fig. 24c). In order to avoid possible damage to the surface during the installation of the Smart Slab, the surface was temporarily left in this state, and the final surface layer of about 1mm thickness was applied after the ceiling was lifted into place

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

Fig. 24: Surface finish process: (a) applying a layer of shotcrete; (b) distributing the material using a modified trowel with distancers; (c) scraping off excess material.

5 Result

Overall, the robotic fabrication process of the mesh was running robustly and without major interruptions. During an average 8-hour working day, 75 cm of wall length were produced, corresponding to an average building speed of 0.25 m^2/h. Over the entire length of the wall, the robot had to be repositioned eight times, whereas the repositioning and referencing process took about one hour each time. Here, the global state estimation, did in the beginning not perform as initially intended: for the first half of the mesh, the camera measurements taken from the fiducial markers, were not sufficiently precise in order to guarantee a geometrically smooth transition of the mesh after repositioning the robot. This lack of accuracy was caused by insufficient camera calibration, however after an accurate calibration procedure was established, a sufficient overall accuracy with deviations below 1 cm and 0.2° was achieved. Accordingly, for the last third of the mesh, the automated tag measurement system was successfully applied [47]. The local state estimation and the integration of a correction routine allowed fabricating the mesh without recognizable internal material tensions or spring-back behaviour. However, after the completion of the mesh, the overall deviation was measured with a Faro Focus3D X 330 laser scanner [53] and deviations of up to 20 mm, especially occurring in regions of increased surface curvature, were measured (Fig. 25a). More specifically, the built curvature was not as pronounced as intended, resulting in a physically slightly smoothed version of the as-planned geometry. However, current improvements of end effector`s bending mechanism have eradicated this error and precise bends are now possible. To achieve this, a counterpart was mounted in the axis of rotation of the bending mechanism around which the reinforcement bar is bent. Initial experiments have already confirmed that the improved bending mechanism can produce more pronounced and accurate bending angles.



(b)

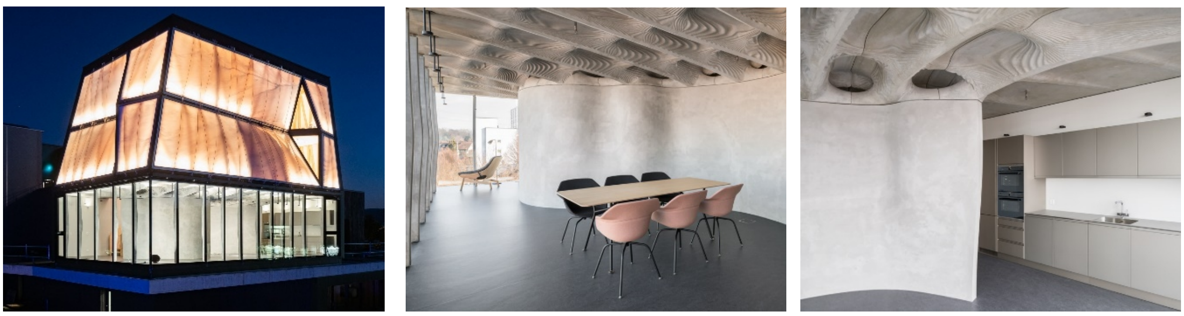
Fig. 25: Quality assessment of the as-built structure: (a) 3D scan error plot, red areas deviate up to 20 mm, orang up to 16 mm and yellow up to 10 mm from the intended geometry; (b) 3D scan of the wall after concreting.

With regards to the mesh filling, the frontal filling technique, using concrete pumps was successful. The initial strategy of using three pumps simultaneously was not realized due to several practical reasons like defects or missing parts. As such, the filling process took 10 hours; however, it is apparent that the fabrication speed is scalable according to the number of pumps used. A video of the process is available in [50]. After concreting, the wall was scanned once more (Fig. 25b), and no further deviations caused by the filling process were identified. Based on this as-built 3D scan of the concreted Mesh Mould wall, the Smart Slab design was computationally generated, securing sub-millimetre precision for the interface of the wall and the ceiling (Fig. 26).

(a) (b)

Fig. 26: Mesh Mould wall:(a) after the cover layer was applied (b) after installation of the Smart Slab.

Regarding the application of the cover layer, the entire wall was finished by four workers during one working day. The custom developed trowels enabled excellent control over surface cover thickness. Local inaccuracies of the surface were smoothed out by scraping off surplus material. After an initial curing time of 4 days scattered light spots were visible on the surface. Shortly after the installation of the Smart Slab and the two-story timber construction, the interior work, including the installation of the façade elements and the elevated floor was carried out. Subsequently a final, 1 mm surface finish was applied to the wall, using a fine grain cement slurry applied with a sponge. The finished DFAB HOUSE is depicted in Fig. 27.



(a) (b) (c)

Fig. 27: Finished DFAB HOUSE; (a) exterior view; (b) interior view into the dining area (c) view into the kitchen. Images by Roman Keller

6 Discussion

One of the main research goals, namely the development of a fully integrated digital fabrication technique, which provides loadbearing capacity in compression as well as in tension, was successfully demonstrated through the 1:1 demonstrator, the Mesh Mould wall on NEST. To this point, no other digital fabrication process for concrete, which offers equivalent design freedom, has yet demonstrated comparable results on the construction scale. For example, state-of-the-art 3D printing technologies with concrete currently rely on the post-hoc placement of reinforcement, at least in the direction perpendicular to the printing plane [8]. Based on the presented experimental work, it can be stated that Mesh Mould structures can be designed using conventional plastic design methods. Strength reduction factors might be considered to address singular aspects of Mesh Mould, such as the shear stresses generated in the continuous reinforcement due to the load transfer between the welded reinforcing bars. Hence, in future research, the loadbearing capacity of the Mesh Mould system, particularly in the direction of the discontinuous rebar could be further improved. In that regard, the addition of steel fibres in the concrete mix has been investigated recently as a potential solution [54]. Additionally, in future research an optimized mesh topology for more efficient load transfer could be investigated. Such improvements could range from optimizing the position and orientation of the discrete rebar to more profound adaptations through which continuous rebar could be placed in both directions.

Another explicit research goal was the elimination of formwork waste. This goal was achieved to a very high extent. Firstly, regarding the offcuts and swarf, which is usually created during the production of customized formwork elements through milling or cutting, and secondly, regarding the subsequent disposal of the unique moulds after a concreting. With the Mesh Mould technology, the mesh remains in the concrete as reinforcement, so that theoretically no waste is produced. However, due to the design of the end effector, there is a small part of each reinforcement bar that cannot be processed. Based on the total weight of the mesh, this results in a waste of approx. 5%, which could be further reduced by a modified feeding mechanism.

An important objective during the development of the Mesh Mould system was to extended the design freedom when building with reinforced concrete. In that regard, the design space of the Mesh Mould process is greatly defined by the robotic setup. Specifically, the in situ Fabricator's vertical reach is limiting the fabrication height to a maximum of 2.9 m. Although the restrictions imposed by this robotic set-up generally limit the design scope of the Mesh Mould system, the design freedom offered was entirely sufficient for the design concept of the DFAB HOUSE. In order to fully exploit the architectural design space of the Mesh Mould system, a robotic setup with an extended built space is required. This might either be achieved with an updated, higher-reach version of the in situ Fabricator, or by changing from in situ fabrication to a larger pre-fabrication setting. In the latter case, larger Mesh Mould structures with more extreme curvatures could be pre-fabricated, and successively be assembled on site before concreting. The first results in prefabrication with increased geometric freedom have already been realized. With these first results in prefabrication it becomes clear that the design space of the Mesh Mould technology can be significantly extended through prefabrication, and that geometries, similar to those shown in the architectural examples in Fig. 1, could possibly be fabricated with the Mesh Mould technology.

In terms of construction costs and productivity a comparative study revealed, that the Mesh Mould fabrication process outperform conventional construction methods for freeform reinforced concrete constructions [15]. In this study a total cost of 54.669 USD for the construction of the double curved wall of the DFAB HOUSE with traditional means was assessed. In comparison, a production cost of 23.262 USD was calculated using the Mesh Mould technology. A process simulation in the above study showed that an additional optimization of the individual process steps, such as an acceleration of the cutting, welding and bending routine through mechanical optimization, path and travel optimization during positioning, or automated rod feeding, could increase production speed, and further reduce production costs by approximately 20%. This cost advantage seems surprising at first, especially with regard to the apparently low production speed of 0.25 m^2/h. However, it is important to consider that the Mesh Mould processes combines a number of process steps, which are traditionally carried out by various trades in a sequential order. In addition to the traditionally manual operations such as producing the custom formwork, bending the steel reinforcement, assembling it into cages, installing the cages in the formwork, pouring concrete, as well as subsequent stripping and cleaning of the formwork, another time-saving advantage of the Mesh Mould technology can be found in integrated design and planning procedures. With Mesh Mould, the production data is generated directly and automatically from design data. In contrast, using traditional processes each trade first has to draft its own specific set of plans, which typically results in additional up-front costs.

Additionally, there are other factors that could further increase the economic as well as environmental and performance of the Mesh Mould technology: first, the current mechanical layout of the robotic end effector limits the fabrication to a minimum distance of 8 cm between the two mesh surfaces. With required minimum concrete cover of 2 cm on each side, minimum wall thicknesses of 12 cm can be achieved. For some applications, this thickness could be further reduced. In this context, the previously discussed architectural example of the material storage of Nervi & Batoli in Via Magliana in Rome should be recalled (Fig. 3b). With wall thicknesses of merely 3 cm this building is an excellent example for an extremely slender construction, enabled by the Nervi's concept of "strength through form". Improvements in the mechanical layout of the end effector could therefore nurture the development of an more expressive formal language of Mesh Mould that is likewise based on structural strength by virtue of geometry. Here novel manufacturing technologies for mechatronics are likely to allow making the end effector smaller and lighter, integrate more functionality into the same volume and weight envelope, and hence allow for more design freedom. Here a realistic reduction of wall thicknesses down to 8 cm is expected.

A further approach for improving the environmental performance of Mesh Mould constructions is the concrete mix design. Currently, a material with an above average cement content was used. Cement, respectively the production of clinker, is a major contributor to carbon dioxide emissions [55]. In order to fully tap into the ecological potential of the Mesh Mould fabrication process, a more sustainable concrete mixture with a lower clinker content should be developed in future research.

7 Conclusion

Within a relatively short amount of time and through interdisciplinary experimental research, Mesh Mould evolved from an initial concept to a fully loadbearing construction system for non-standard reinforced concrete constructions. The main research goal, namely the development of an integrated digital design and manufacturing workflow for free-form, load-bearing concrete components, with increased material efficiency and a reduction of construction waste and fabrication costs, was validated through the final demonstrator, the Mesh Mould wall within DFAB HOUSE on NEST.

The core contribution of this research to the field of digital concrete fabrication is the development of a holistic construction system. In contrast to other contemporary automated fabrication approaches in the field of non-standard concrete construction, Mesh Mould equally considers the interdependency of all three components – reinforcement, formwork and cementitious matrix from the very beginning. By unifying formwork and reinforcement into a single robotically controlled construction system, it allows fabricating differentiated loadbearing reinforced concrete elements, while substantially reducing construction waste as it is commonly caused by one-of-a-kind formwork. Moreover, several methods for digital design, and techniques for non-standard robotic fabrication and material manipulation have been developed over the course of this research. These digital design and fabrication methods incorporate the specific constraints of the fabrication process and can hence be characterized as "fabrication-aware design tools". Accordingly, a multitude of constraints, which are arising for instance from a certain mesh typology, from the material behaviour or from the mechanical design of the robotic end effector, are integrated into the design software. Based on those constraints, the computational design workflow confines the design space exactly to those geometries, which are producible with the respective fabrication setup, and indicates regions of potential conflicts such as tool-material collisions. As a result, extensive post-rationalization as it is often necessary in conventional and sequential design and fabrication workflows can be substantially reduced.

In summary, the Mesh Mould construction system contributes to the greater efforts of a global interdisciplinary community of researchers and practitioners to foster a digital building culture that reflects the technological possibilities of the digital age. The Mesh Mould research project thus provides first evidence of the emerging potential of bringing the design, planning and construction phases closer together, allowing for a resource efficient, individualised building production through industrialized means.

8 Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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