Overcoming Repetition: Robotic fabrication processes at a large scale

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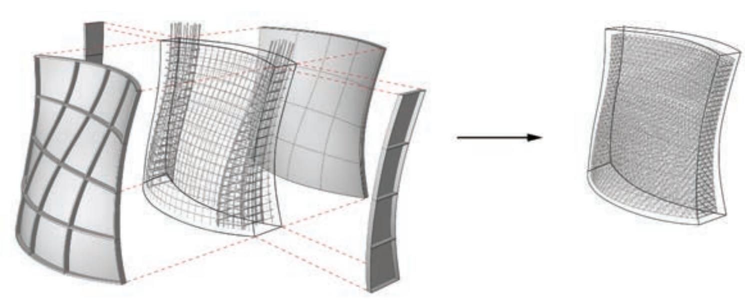
In the context of the Future Cities Laboratory (FCL) of ETH Zurich, the Professorship for Architecture and Digital Fabrication of Fabio Gramazio and Matthias Kohler has set up a robotic laboratory to investigate the potentials of non-standard robotic fabrication for high rise constructions in Singapore. The high degree of industrialisation of this dominant building typology implies standardisation, simplification and repetition and accounts for the increasing monotony evident in many Asian metropolises. The aim of this research on material systems for robotic construction is to develop a new and competitive construction method that makes full use of the malleable potential of concrete as a building material. A novel, spatial, robotic "weaving" method of a tensile active material that simultaneously acts as the form defining mould, folds two separate aspects of concrete -reinforcement and formwork-into one single robotic fabrication process (see Figure 1). This in-situ process could permit the fabrication of structurally differentiated, spatially articulated and material efficient buildings.

1. INDUSTRIALISATION OF THE BUILDING SITE

Compared to other manufacturing sectors the degree of industrialization in architecture and the building industry is rather low. Even though components and building elements of architecture, such as bricks, steel beams and prefab concrete panels, are industrially prefabricated, they are usually not automatically assembled. Human labour clearly predominates in the assembly process on site. This is a fundamental difference to other industries, like e.g. the automotive industry, in which the entire process from production of parts to final assembly is industrialized and often fully automated. The reason for this is conspicuous: buildings are not industrial mass products, but most often unique and customized for the individual needs of a client and specific site. Additionally, the prefabrication of large building elements is constrained by transportation and therefore large elements are generally manually produced on-site instead of being industrially prefabricated in a factory. Despite these unfavourable preconditions for the complete industrialisation of construction, automation processes have been subject to research since several decades. Starting with the prefabrication of building components, there has been a noticeable trend towards the automation of the entire assembly process on the building site. The first ideas for rationalization through mass production of building elements, which have been developed in the early 1930s, have been implemented to a larger extend only in the 1960s and 1970s. In the following decades, most notably in the 1980s and 1990s in Japan, the absence of qualified labour in concurrence with the enhancements in data handling and logistic control has driven an increased research in on-site construction automation [1]. These automation endeavours have been successful only to a certain extend. The primary goal to reduce human labour was achieved, but in turn the automation process required such high degree of standardization so that resulting architecture was too inflexible and repetitive to sustain the demands of planner, users and changing economic circumstances. Further technological advancements at the beginning of the 21st Century, such as ubiquitous computational power and the availability of cheap off-shelve industrial robots[1], have extended the field



► Figure 1: Conventional formwork and Mesh-Mould.

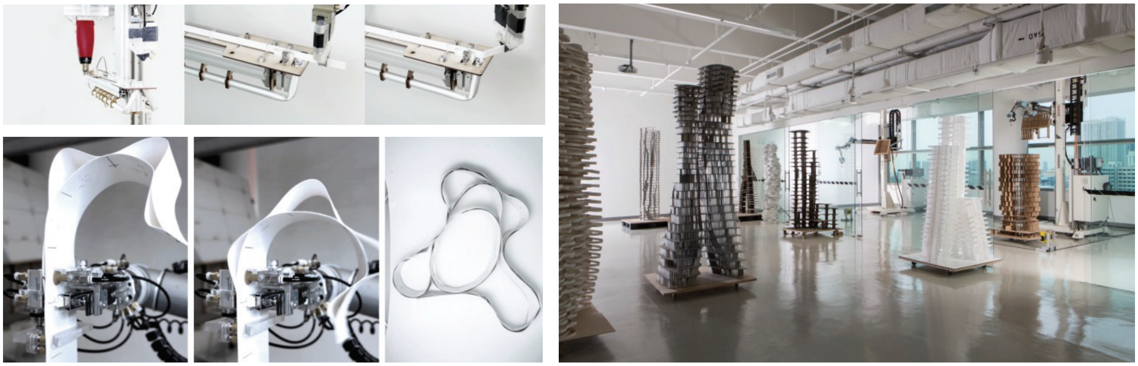
[1] According to the International Federation of Robotics the number of robots in operation ranges in between 1.1 and 1.4 million globally. http://www.ifr.org/industrial-robots/statistics/(accessed 25.07 2013). Despite their abilities, they are mostly performing repetitive tasks.

of possibilities for computer controlled fabrication and new architectural expressions dramatically [2]. The combination of computational power, advanced sensor technology and the high flexibility of the industrial robot now allow for an application of the robotic systems directly on the building site [3]. Robotic in-situ fabrication has a potential to close the circle for a fully industrialized construction process and offers new modes of production which reach beyond rationalization and mere automation.

2. DESIGN OF ROBOTIC FABRICATED HIGH RISES

In the realm of architecture, and especially with regards to mass housing, the high rise is often seen as the embodiment of industrialised construction and mass production. This particularly applies to the many fast growing Asian metropolises. In this context the unique setup of the research project *Design of Robotic Fabricated High Rises at the Future Cities Laboratory* [4] in Singapore allows investigations into the potentials of robotic fabrication for the design and construction of high rises. The particular condition of mass housing in Singapore offers an optimal test bed for the research on innovative building processes: An increasing population growth and the scarcity of land challenge Singapore to deal with further densification, the high rise is an obvious solution at hand. By launching the Building Control Act [5], the Singapore government expressed its support for the application of industrialized and automated building processes in order to achieve a higher overall productivity, better construction quality, and to be less dependent on manual labour. These preconditions are favourable for the investigation of computer controlled fabrication processes, as their strength and benefits have multiplier effects: In contrast to pure automation, the *flexibility of robotic fabrication processes* has the potential to defy the prevailing "one size fits all" approach of standard high rise constructions in Singapore; On a programmatic level it can promote *substantial variation in the structure* in order to accommodate more diverse architectural programs; In terms of material efficiency, robotics could allow the fabrication of structurally optimised and geometrically complex building components well adapted to the forces that act upon them.

The underlying research question – how this new digital fabrication paradigm, is articulated in the architectural design and construction of high rises – is investigated on two distinct but mutually influencing levels of research. A two year long design studio, consisting of master students from ETH Zurich and NUS Singapore, explores how robotic fabrication enables new high rise typologies. Focusing on 1:50 scale the students develop custom fabrication processes based on the intrinsic properties of the robot and in conjunction with other architectural parameters like site, programme and structure (see Figure 2).



▲ Figure 2: Two selected fabrication concepts designed by the students: Top left: Bending setup. Acrylic stripes are fixed in a linear rail and pulled forward to their designated bending position. The material gets heated by a hot air gun to 550°C for 10 seconds. The robotic arm can now bend the material to any angle between 0° and approximately 160°. After the deformation the material gets cooled down by air pressure. Students: Kramer, Stünzi.
Bottom left: Robotic stapling process. Initial study model of robotically produced geometries. Design Research Studio 2012 – Phase 2, Ernst, Rickhoff, Strohbach.
Right: Series of 1:50 models of high rises in the studio context, Design Research Studio 2012

The search for progressive high rise typologies correspondingly challenges innovations concerning material aspects. This second strand of research is conducted on PhD level and concentrates on 1:1 material- and construction- processes for robotic fabrication on a large scale. On the grounds of concrete's workability in fresh state and the various ways of forming it, concrete has been evaluated as a material with high potential for robotic fabrication and material innovation. The project's working hypothesis is that the industrial robot, which can precisely and swiftly execute spatial movements regardless of complexity, could unlock the full plastic potential of concrete as a building material. Considered globally, concrete is the most used man-made material in building-construction today. Twice the mass of concrete is used as the total of all other construction materials together, this includes wood, steel, aluminium and synthetic polymers[2]. In conventional concrete constructions the amount of labour involved for the installation of formwork and reinforcements accounts for over 50% of the total cost of a structure[3] and rises exponentially with increasing geometric complexity. In an attempt to reduce these costs many concrete structures tend to be simple and repetitive, thus neglecting the structural and aesthetic potential of this versatile material. This practice of simplification and repetition can be

[2] The World Business Council for Sustainable Development published these numbers on their webpage: http://www.wbcsdcement.org/index.php/about-csi/explore-cement?start=2 (accessed 6.6 2013)
[3] This number has been announced in a joint publication of the National Council of Structural Engineers Associations (NCSEA), the American Council of Engineering Companies (CASE) and the Structural Engineering Institute (SEI) of American Society of Civil Engineers http://www.structuremag.org/article.aspx?articleID=423

◀ Figure 3: Public housing, Singapore

hold accountable for the increasing monotony of the built environment, especially noticeable in many Asian metropolises. (See Figure 3)

Moreover, curvilinear geometries do not only widen the scope of formal expression, but likewise are structurally more effective (See Figure 4). However, with conventional fabrication methods the cost of fabrication exceeds the savings of material.

◀ Figure 4: Reiser + Umemoto O-14, Dubai (RUR Architecture PC 2007)

3. FORMWORK-FREE FABRICATION

Academia and industry have discovered the high potential of robotic fabrication of concrete structures, and research in this field has recently taken a great leap forward. Especially with regards to computer controlled processing there is a strong and persisting trend towards the extrusion of concrete, a process which eliminates the need of formwork entirely[4]. However formwork-free fabrication processes of concrete structures are largely depending on the material properties and their controllability. The hydration process of cementitious materials is difficult to control and consequently imposes large limitations on this fabrication method.

Polymers on the other hand can be precisely controlled; nevertheless they are not particularly suitable for loadbearing constructions. In the following sections it will be discussed how spatial extrusion of polymers can

[4] With regards to automation, this trend corresponds with the general finding from the manufacturing industry that material processes are easier to automate if a material is in liquid state [15]

► Figure 5: Contour Crafting, University of Southern California [6]

be used for the fabrication of geometrically unconstrained formwork and how through co-extruding of a tensile active filament this formwork could simultaneously act as reinforcement.

3.1. Extrusion of Cementitious Materials

Ten years ago the layer based extrusion of cementitious materials has raised hope for an entirely waste free and geometrically unconstrained fabrication method. Researchers at University of Southern California [6] and University of Loughborough [7] have set up large research facilities with concrete extrusion heads mounted on large gantry cranes in order to investigate concrete printing at building-scale (See Figure 5). Both approaches are linearly scaled-up versions of conventional 3D printers, which raises several difficulties: In order to achieve smooth surfaces, the layer height needs to be sufficiently small, which cubically increases fabrication time [8]. The hydraulic binding process of concrete is very difficult to control and affects load bearing capacity, layer adhesion and curing time. Particularly the latter is a determining factor for the printing speed of concrete. Another unresolved issue is the integration of reinforcement.

In contrast to the horizontal, layer based extrusion; Smart Dynamic Casting focuses on the vertical slip-forming of concrete columns[5]. The research project tackles the aforementioned problems of limited material control during the process of hydration. Smart Dynamic Casting introduces the use of sensors to monitor the curing process and receive feedback about the state of the material during the process of casting. A careful orchestration of precise timing, sensor feedback and controlled spatial movement makes it possible to form concrete in the delicate moment of state change [9]. Even though a remarkable level of material control is achieved, it becomes evident that the design freedom is limited by the properties of the material itself. In this regard deviations from the vertical axis are only possible as long as the resulting tensional forces stay within a certain threshold.

[5] The PhD research project combines conventional slip-forming technique with the advantages of digital fabrication. The research is conducted by Ena Lloret Kristensen at the chair for Architecture and Digital Fabrication, Prof. Fabio Gramazio and Prof. Matthias Kohler in cooperation with: Prof. Dr. Robert J. Flatt (PI), Prof. Dr. Hans Jürgen Herrmann; Civil, Environmental and Geomatic Engineering (D-BAUG), Inst. f. Building Materials (IfB), ETH Zürich; Dr. Peter Fisher, Dep. Health Sciences & Technology (D-HEST) [16]

In conclusion, cementitious materials are less than ideal for fast, precise and geometrically unconstrained formwork-free fabrication processes. The commercial success of concrete extrusion/printing processes largely depends on improvements in material technology.

3.2. Extrusion of Polymers

In contrast to cementitious materials, polymers can be engineered in order to meet the exact requirements of a fabrication process and are today used for a wide variety of applications.

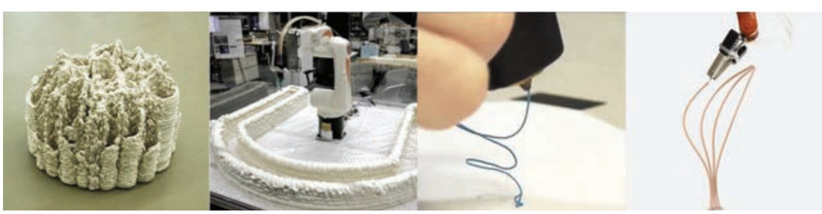
In an architectural context the robotic extrusion of Polymers has first been explored by the Professorship for Architecture and Digital Fabrication at ETH Zurich in 2007 [10]. An off-shelve polyurethane (PU) foam, usually used for insulation purposes, was poured layer-wise by an industrial robot up to height of 1.5 m. Although the control on the expanding foam was very limited, these first experiments have demonstrated the potential of robotic extrusion for architecture.

In 2012 the Mediated Matter Group at MIT used a similar technique for the robotic fabrication of lost concrete formwork [11]. Layers of PU foam are successively sprayed on top of each other until they form an approximation of the desired geometry. In a subsequent step the imprecise and rough surface is smoothed by milling it to the desired end shape and the formwork is finally filled with concrete. The formwork then remains in place and acts as thermal insulation.

In contrast to polyurethanes, thermoplastic- and thermosetting-polymers are controllable to such a rate that through accurate local temperature control free spatial extrusions become possible. Recently, research projects have been conducted, which use this capacity to overcome layer based disposition.

The 3Doodler, a PLA and ABS extruding pen allows for the first time to entirely leave the 2D plane and enables drawing in space [12]. The project builds up on conventional 3d printing technology with additional air cooling. Instead of a computer controlled motion path, the path control is put in the hand of the user. The challenge to precisely control the material in space is an exciting aspect of the concept of this toy.

Mataerial [13], a research project conducted at IAAC in collaboration with Studio Joris Laarman, follows a similar line of inquiry, but puts the extruder back into the digitally controlled hand of the robot. Instead of



◀ Figure 6: Extrusions of polymeric material: The Foam [10], Building-Scale 3D Printing [11], 3Doodler [12], Mataerial [13] using thermoplastic polymers the material used is a two component thermosetting which hardens under heat. The project demonstrates that by slow and precise robotic guidance, controlled spatial extrusions of relatively wide spans (1.5m, at a speed of 0.3m/min) are possible. The use of light porous material additionally enables extreme cantilevers, which would not be possible with dense structural materials like concrete.

3.3. Synthesis:

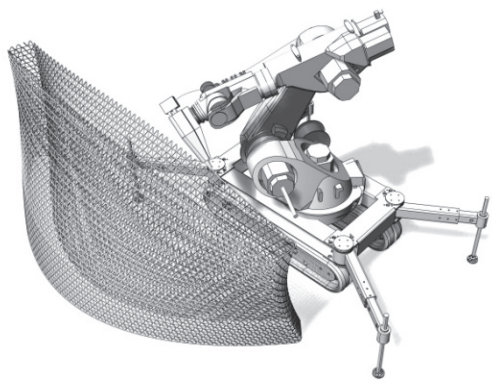
The decision to avoid the direct processing of concrete but to focus on the robotic production of formwork instead was motivated by the fundamental difficulties encountered in printing a material with hydraulic properties as well as by the pragmatic insight that for robots it is easier and more efficient to build lightweight structures than to handle the whole mass of the concrete structure.

An analysis of the existing formwork technologies led to the insight that one specific system, called "Leaking Formwork" [14], has a particularly high potential with regards to robotic fabrication. Its basic principle works as follows: Concrete is poured into a perforated formwork, which is built up from corrugated plastic panels. The concrete protrudes through the perforations in the surfaces and covers up the panels. In a final step the protruded material gets manually troweled in order to create a smooth concrete surface (See Figure 7).

► Figure 7: Leaking Formwork by Forma-tech [14]

3.4. Robotically extruded Polymers as Concrete Formwork

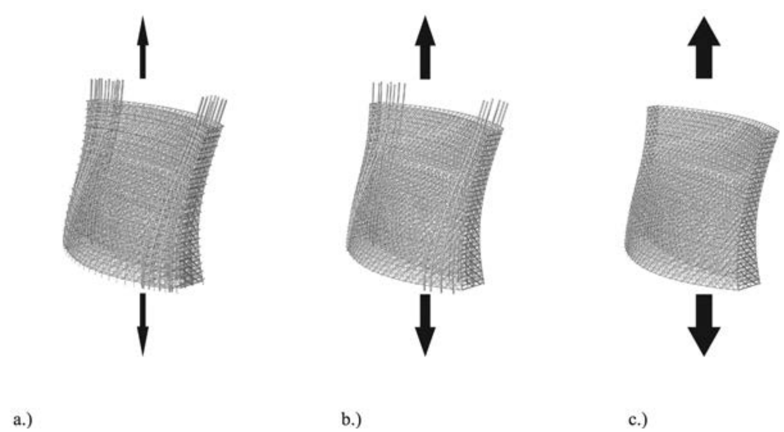
This simple and efficient material system holds a great potential when crossbred and augmented with the logic of robotic fabrication. If the perforated formwork is directly extruded in-situ as three dimensional spatial meshes by the robotic arm, instead of being composed of discrete prefabricated panels, the system is liberated from planarity or single curvature (see Figure 8). The liberty of free spatial extrusion allows fabricating three-dimensional formwork meshes well adapted to the forces that will act upon them. A local differentiation of the mesh, which can be achieved by varying the size of the single stiches and the thickness of the



◀ Figure 8: Robot extruding mesh

extrusion, can accommodate the changing hydrostatic pressure during the pouring process, which decreases from bottom to top, and thus control the protrusion of the material through the openings.

In addition to the primary goal of unlocking the full plastic potential of concrete as a building material, the research aims at activating the extruded polymer meshes as structural reinforcements. Their strength could be increased by the co-extrusion of tensile active filaments and a significant amount of steel reinforcement could be saved. By going beyond the simple automation of human labour, this process activates the full potential of robotic fabrication to enable material systems, which would not be otherwise feasible. In order to get a better hold on the ambitious overall aim, the substitution of the steel reinforcement is implemented in sequential steps. The first step is focusing on the form-defining capacity and the spatial extrusion of polymers (see Figure 9a). A subsequent step aims at substituting the secondary reinforcement, which prevents surface cracking in concrete elements (see Figure 9b). In a final step fabrication technique and material research are to converge to substitute the entire tensional reinforcement of the concrete element (see Figure 9c).

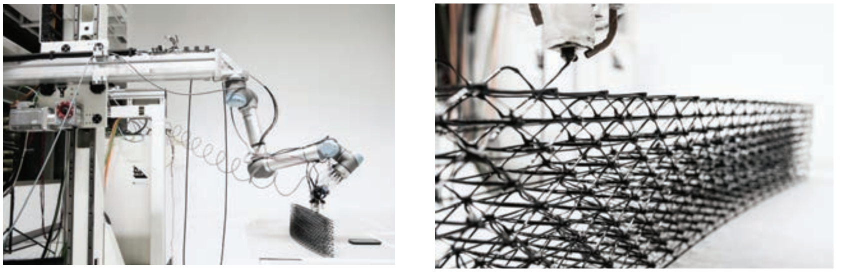


◀ Figure 9: Increasing tensional capacity

4. FABRICATION EXPERIMENTS: SPATIAL EXTRUSION WITH THERMOPLASTICS IN SCALE 1:1

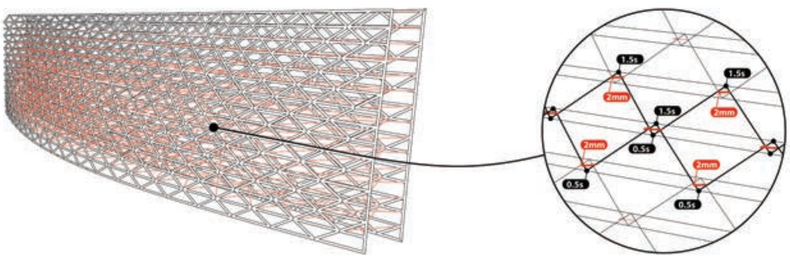
The experiments conducted until now offered insights about the potential of spatial, non-layer-based extrusion of Polylactic Acid (PLA) for the fabrication of spatial meshes. The availability of a standard 3mm PLA filament allowed running the first experiments by using off-shelf 3D printer extruder- and feeder-components. The integration of a custom cooling system based on pressurized air, that locally hardens the material in the moment it is extruded, has been key to the ability to extrude material freely in space. The motion path for the robot was directly generated by a custom algorithm generating 3-dimensional mesh structures from any arbitrary set of surfaces. The samples created were doubly curved meshes with dimensions of approximately 600 * 500 *250 mm, a stich size of 30 * 20 * 20 mm, extrusion diameter of 2 mm and a total volume fraction of the mesh of 2.5% (see Figure 10). The stich dimensions of these first samples represent approximately 1:1 scale; however the global geometry remains a fraction of a larger non-specified element. Stich dimension, extrusion thickness and global geometry will be adjusted according to the results of subsequent concrete pouring tests. Additionally, the relatively low feed rate of 1 m/min will be addressed during the further development of the process.

► Figure 10: Spatially extruded meshes



5. FIRST RESULTS

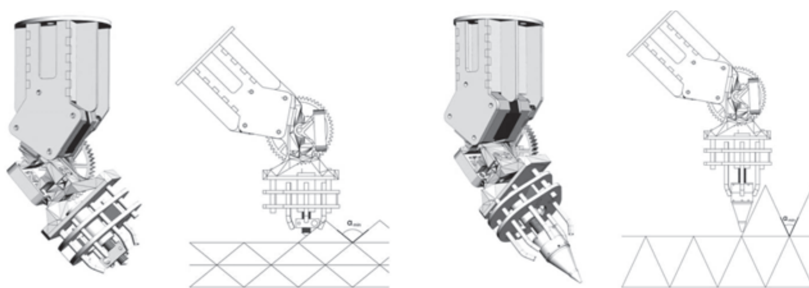
The incorporation of the dynamic material behaviour into the path generating script has been pivotal for the successful fabrication of fully connected and stable meshes. Several experiments were conducted to understand the correlation of heating, cooling and hardening behaviour of the material and their relation to feed-rate, cantilevering distance and motion speed of robotically controlled extruder. The findings resulted in the implementation of slightly super-elevated amplitude, short stops for cooling and hardening, increasing and decreasing air pressure for certain inclination



◀ Figure 11: Adjustments of path in order to meet desired outcome

angles and the selective disposition of additional material as connection knots (see Figure 11)

While some constraints can easily be solved by motion planning, others require adjustments in hardware. The collision-free extrusion of material at steeper angles, for example, can only be enabled by a custom design of the extruder head (see Figure 12). The experiments have shown that increasing the extrusion rate in order to speed up the process requires a more efficient cooling mechanism.



◀ Figure 12: Extruder head with air cooling: Based on standard components (left) and with custom extruder nozzle (right)

6. FURTHER STEPS

The previous experiments have demonstrated the general technical feasibility of the fabrication process. The extrusion of complex meshes displaying horizontal cantilevers, overhanging angles of inclination and double curvature with small curvature radii, demonstrated the versatility of this method. However at this early stage of research several important fabrication parameters have not yet been included. Three key challenges have been identified as drivers for the forthcoming research phases:

1. Fabrication speed
2. Tensile strength of the extruded material
3. Transmission of the forces across the extruded mesh

The fabrication speed is mainly depending on the hardening behaviour of the extruded material and can be controlled through local cooling. Several cooling strategies are currently under development and are progressively integrated into the next generation of tool heads. In future experiments water will substitute air as a more efficient heat-transfer medium and even nitrogen is considered for rapid cooling. In order to substantially accelerate the process, especially when scaling it up to real scale, strategies of parallelisation like the incorporation of multiple extrusion heads will have to be considered. The tensile strength of the extruded material can be significantly increased by co-extruding a high-strength filament. Carbon-, glass-, bamboo- and basalt-fibres, as well as steel wire are materials currently under consideration.

Research in the field of 3D-textile-reinforcement for ferrocement building elements provides an insightful point of reference, not only with regards to different materials and material properties, but also with regards to the third key challenge. The transmission of forces across the extruded meshes largely depends on the force-locking connection between the extruded strands. Various weaving, knitting, crocheting techniques are being explored and evaluated against their applicability for a robotic fabrication process. This step goes hand in hand with the development of the parallelization strategy as mentioned earlier on. One possible strategy, which is evaluated at this point of time, is the development of an extrusion head that extrudes multiple strands and concurrently intertwines them through rotation. The entire development happens in feedback loops with concrete pouring tests and will need continuous adjustments of the material and fabrication.

7. CONCLUSION

Combining formwork and reinforcement into one robotically fabricated material system promises far-ranging implications: On the level of building site organization the various crafts and professions involved in the process of concrete construction can be folded into one. A typical concrete process involves the prefabrication of formwork and rebar, transportation to the site and site logistics, bending, placing and connecting rebar, installation of formwork, concreting, disassembly of formwork, cleaning of formwork and finally surface finishing. Most of these processes can be shortcut by the in-situ extrusion of the reinforcing formwork[6]. This synthesis of processes suggests that the complexity of building elements and structures can be increased while at the same time organizational complexity on the building site is being reduced. Beyond the aspect of merging processes, in-situ robotic fabrication allows for dynamic response to the imprecisions and tolerances often confronted with on the building site. Moreover, being an additive manufacturing process, the production of waste is reduced to a minimum while the material efficiency of the process is further enhanced by the double agency of the material system. But most importantly the

[6] The short-circuiting of long and linear sequences of labor in order to dramatically simplify processes is coined "reproduction" and is described as the fifth degree of Industrialization [17]

proposed process allows for substantial variations within a structure. Gradual deviations of grid dimensions can be informed by criteria such as structural optimization as well as by the incorporation of more diverse architectural programs. Since the fabrication process can directly inform the design and vice versa, the classic sequential notion of design, planning and execution stages is challenged. Particularly with respect to mass housing in SE-Asia, the cost of construction is the most determining parameter; with a more flexible fabrication system though other architectural design criteria could regain more importance.

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