ADAPTIVE MODULAR SPATIAL STRUCTURES FOR SHOTCRETE 3D PRINTING

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Abstract. This paper presents a modular, digital construction system for lightweight spatial structures made from reinforced concrete. For design and fabrication, a digital workflow is presented, which includes the rationalization of a freeform geometry into adaptive spatial modules made up entirely of planar components. For fast and precise fabrication, these components are 3D printed using a novel 3D concrete printing technology called "Shotcrete 3D Printing". The ongoing research is demonstrated by an initial real-scale prototype of one exemplary spatial module. Lastly, the paper provides an outlook into future research, which is necessary to make this digital construction system applicable to the real-scale construction of large, wide-spanning structures.

Keywords. Robotic Fabrication; Digital Construction Systems; Shotcrete 3D Printing; Modular Structures.

1. Introduction

Spatial structural systems, such as lattice structures and space frames, are highly efficient load-bearing structures, which are characterized by a good ratio of material consumption to space spanned. This feature makes them particularly suitable for long-spanning, column-free constructions, as for example halls, terminals, or hangars. Moreover, as spatial structures consist of a large number of discrete structural members, they are geometrically well adaptable by locally altering the length and angle of individual members. Accordingly, spatial structural systems are particularly well suited for the realization of free-form geometries as for example recently demonstrated in the Heydar Aliyev Center by Zaha Hadid Architects (Zaha Hadid Architects 2012), the ArcelorMittal Orbit by Anish Kapoor and Cecil Balmond (Studio Balmond 2012) or the Shenzen Bao'an International Airport by Studio Fuksas (Studio Fuksas 2013). Due to the reason that the elements of a spatial structure must bear both, tensile as well as compressive forces, they are today predominantly constructed using isotropic construction materials like steel or aluminum. Spatial structures constructed in reinforced concrete, on the other hand, are less common (Schätzke 2015). There

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 2, 363-372. © 2019 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

are mainly two reasons for this: On one hand, this is due to the high costs involved in constructing the geometrically complex formwork, and on the other hand due to the constructive and visual “heaviness” of concrete structures, which is caused by the minimum concrete cover necessary to protect the steel reinforcement. Today technological innovations like computational design and calculation tools, novel robotic fabrication techniques, as well as innovative material composites like textile reinforcement (C3 - Carbon Concrete Composite e. V. 2017) and high performance concrete (Ductal 2015), could possibly pave the way for the application of reinforced concrete for geometrically complex spatial structures. However, despite the technological innovations, the challenge today remains to develop adequate digital construction systems, which seamlessly integrate these innovations and which negotiate between interdependent factors like structural efficiency, fabrication efficiency, and material properties. The goal of this ongoing research project is the development of an integrative digital construction system for adaptive modular spatial structures in reinforced concrete, which equally considers fabrication constraints, structural performance, material properties, construction site logistics, as well as economic and ecological aspects. In view of that, this paper describes a digital construction system and a digital workflow, in which a freeform geometry is first rationalized into planar panels, secondly developed into spatial modules, and which can finally be fabricated rapidly and without causing construction waste using 3D concrete printing technology.

2. Background

Today a number of research groups investigate the use of reinforced concrete for the realization of structurally optimized and hence geometrically complex lattice constructions. For the realization of such structures, most fabrication approaches today focus on the fabrication of the concrete lattice formwork. Three different approaches are described in the following paragraphs: The research project “Hedracrete” of the “Polyhedral Structures Laboratory” of the University of Pennsylvania investigated spatially complex polyhedral structures developed on the basis of three-dimensional static graphics (Figure 1a). This method is exemplary for structural efficiency, expressive forms and the minimal use of material. Tectonically, the Hedracrete Pavilion consisted of 129 individual Glass Fibre Reinforced Concrete elements, including 54 compression members, 30 tension members as well as 45 three-dimensional concrete nodes. The formwork of the individual lattice elements was CNC milled, whereas each of the 129 parts was composed of at least two CNC milled parts (Akbarzadeh et al. 2017). The project indicates, that realizing highly efficient structures, still involves considerable efforts in the fabrication of the lattice formwork, and moreover that form-work waste remains an inevitable aspect when realizing highly differentiated constructions. Maintaining fabrication efficiency while being structurally highly efficient was the starting point of the Opticut research project (Søndergaard et al. 2019). This research project explored methods for efficiently fabricating topologically optimized structures by applying robotic abrasive wire cutting techniques for EPS formwork. Here, the individually cut lattice formwork parts serve as inserts for standardized concrete formwork. As the final demonstrator, the research group realized a geometrically complex, topologically optimized pavilion with dimensions of 20 x 3 x 5 m (Figure 1b). Compared to multi-axis milling, the hot wire cutting process is more than 100 times faster and provides smoother surfaces. However, despite the considerably improved fabrication efficiency, also here large quantities of formwork waste are created. A strategy for eliminating formwork waste to the largest extent possible was recently demonstrated in a project by Xtree (Gaudillière et al. 2019). For this project, the formwork and temporary support structure for a 4 m high, truss-like column, was 3D printed with concrete in four individual segments. After curing, the segments were stacked on top of each other, filled with concrete and the temporary support structure was removed (Figure 1c). The structure´s high geometric complexity made the integration of conventional reinforcement challenging. Hence, the structure was filled with Ultra-high Performance Concrete, which provided, sufficient tensile strength for this particular application. For the proof of the load-bearing capacity, the printed lattice formwork was structurally treated as lost formwork. Despite being one of the first applications of 3D printing with concrete in construction, the project also makes two of the major challenges evident: Firstly, integrating structural reinforcement into the additive manufacturing process remains problematic, and secondly, 3D printed construction elements are not yet approved for the application as structural elements.

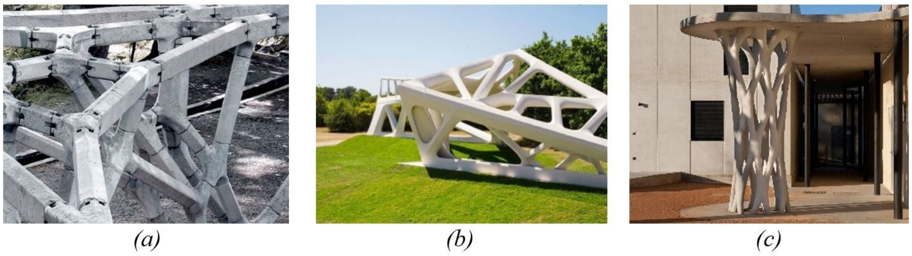
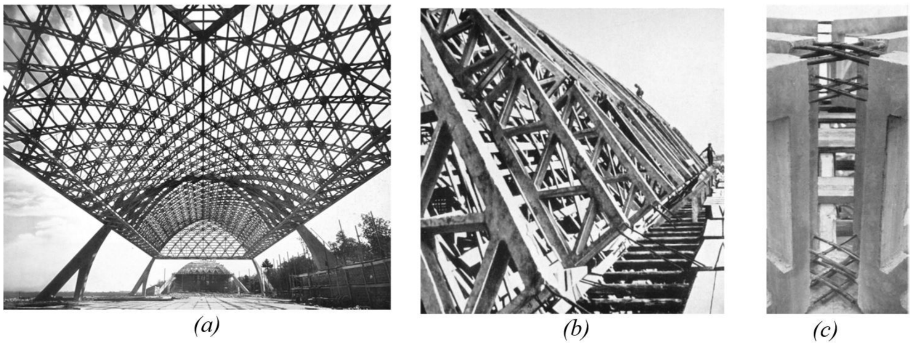

(a) *(b)* *(c)*

Figure 1. Contemporary examples for spatial structures in reinforced concrete(decreasing complexity, increasing fabrication efficiency): (a), Heptacrete; (b) Opticut; (c) column in Aix-en-Provence.

The three examples show that, despite the technological advancements, the fabrication of spatial structures in reinforced concrete still remains labour, time, and waste intensive. However, for a fabrication and material efficient design of spatial structures in reinforced concrete, clues can be taken from the past. Pier Luigi Nervi, for example, developed a series of aircraft hangars for the Italian Air Force based on a highly efficient lattice shell system composed of prefabricated, spatial truss girders (Greco 2008). For the construction, Nervi developed a system of 3 m long and 90 cm deep, planar, prefabricated concrete trusses which were assembled on site to form a diamond-shaped vault structure.

After assembling, the trusses were monolithically joint by casting concrete into the gaps between the trusses (Figure 2).



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

Figure 2. Pre-fabricated Airforce hangars, Pier Luigi Nervi, Orvieto, 1939: (a) interior view of the lattice shell before the planking; (b) prefabricated truss girders during assem-bly; (c) detail of the joint before casting.

By exclusively using identical, planar truss girders, Nervi was not only able to save considerable amounts of material, weight and time but also he was able to reuse the formwork and hence reduce construction waste. The drawback of using merely identical components is clearly a restriction of design freedom. However, with new digital design and optimization tools, novel high-performance materials and novel robotic fabrication methods, this particular limitation can be dissolved. As such, this research takes Nervi‘s system as a reference and proposes a spatial structural system, that equally considers structural efficiency, fabrication productivity, as well as ecological and economic factors.

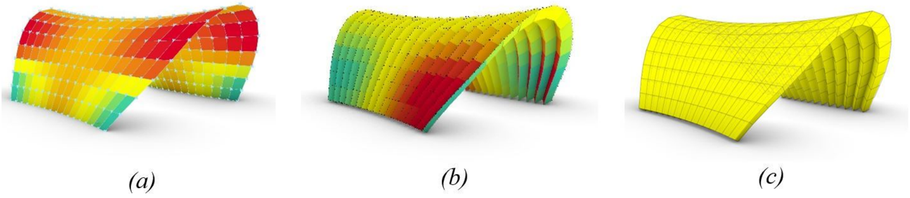
3. Methods

The overall concept of the construction system is based on the following digital workflow: Firstly, a freeform geometry is rationalized into spatial modules, consisting of planar components. Secondly, the spatial modules are digitally unfolded, the fabrication paths are generated, and the components are 3D printed as planar elements. Preconfigured reinforcement is manually placed during the printing process. Thirdly the edges, along which the components are connected are post-processed while the concrete is still in its green state. Subsequently, the components are assembled into spatial modules which can finally be assembled into a shell configuration.

3.1. COMPUTATION:

3.1.1. Segmentation and planarization

Based on the constraint that all elements in the structure have to be planar, a workflow was developed that rationalizes a given freeform NURBS surface into spatial modules consisting of exclusively planar components. Initially, a given input surface is divided into quadrilateral components, which results in predominantly double curved components (Figure 3a). In the next step, the components are planarized using a physics solver implemented in Kangaroo 2 for Grasshopper. Each of the newly created planar quadrilaterals subsequently serves as the basis for the development of the spatial modules. For this, the mean curve of the long surface edge is generated and subsequently offset in the direction of the surface normal. Based on the edge curves and the newly created mean curve, two additional surfaces are created, providing structural depth. These surfaces, however, are yet again not planar (Figure 3b). Hence, the two resulting surfaces also have to be rationalized, however this time with two additional boundary conditions. First, the resulting surfaces have to be connected to the initial planar quadrilateral and secondly, the module has to be connected to the next module on all edges (Figure 3c).



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

Figure 3. Module generation: (a) initial surface subdivided into double curved quad-rilaterals with colours indicating the double curvature; (b) planarized quadrilateral grid with double curved surfaces providing structural depth (c) planarized quadrilat-eral grid with planar spatial structure, the single colour indicates planarity.

3.1.2. Optimization and Preparation

In a final stage, the planar quadrilaterals are transferred into a spatial lattice structure, which is locally adapted to the specific loading condition. For this, the module edges are extracted and the stresses are calculated using Karamba for Grasshopper. Depending on the structural load, the thickness of the element is calculated and the geometry is generated for all modules (Figure 4a). In a final step, each module is unfolded, positioned and translated into fabrication data. For this, an offset of the outlines creates the input for the robot path. In order to simulate the robot‘s movement, the plugin “Robots” for Grasshopper is used (Soler 2017). The coordinates and the tool speed are translated into a G-code legible for the Siemens Sinumeric, which is controlling the robot and CNC mill.

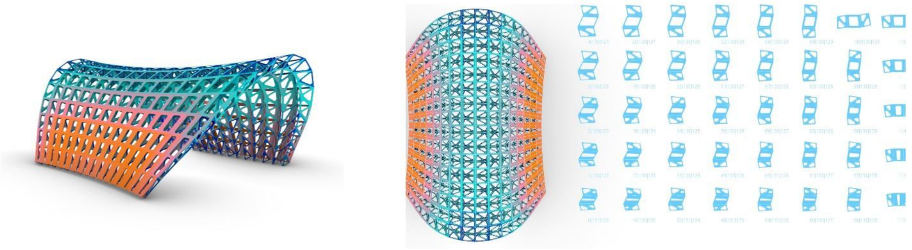

(a) *(b)*

Figure 4. Final geometry: (a) Planar and structurally adapted structure with thicker parts marked in orange and more slender members in blue; (b) top-view of the structure and digitally unrolled modules.

3.2. 3.2. FABRICATION:

3.2.1. Robotic setup:

For fabrication, the unique Digital Building Fabrication Laboratory (DBFL) of the Institute for Structural Design at TU Braunschweig was used. The DBFL is a large scale robotic fabrication facility consisting of a gantry system with two independently controllable manipulators, firstly a six-axes Stäubli TX 200 robot, and secondly a three-axes Omag milling application. The overall cooperative build space embraces 10.5 x 5.25 x 2.5 meters. As such, the DBFL facilitates the production of largescale structures, both by subtractive machining, as well as by additive manufacturing processes.

3.2.2. Printing method:

For the printing process, the Shotcrete 3D Printing (SC3DP) technology, which was previously developed by the authors was applied (Lindemann et al. 2019). This novel technique differs from conventional 3D concrete printing by the fact that the material is not simply extruded, but spayed with pressure in order to build up a three-dimensional structure. The advantages compared to conventional 3D printing are, firstly, a superior layer adhesion, secondly, the ability spray around, and hence integrate, reinforcement, and thirdly, the potential to spray against vertical surfaces and overhangs.

3.2.3. *Fabrication:*

Prior to printing, a planar wooden baseplate was installed in the workspace of the DBFL. The fabrication data for each of the module‘s components was uploaded, and the concrete mixing process was started. Each of the module‘s three components was printed separately in three consecutive layers. After the first two layers were printed, 8 cm wide and 100 cm long strips, cut from a larger carbon fiber reinforcement grid (sglgroup 2017), were manually placed on the top layer. Subsequently, the last layer was sprayed on top of the previous layers, embedding the carbon fiber reinforcement into the structure (Figure 5a).


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

Figure 5. Fabrication process: (a) Spraying of the elements; (b) cutting of the edges in the green state of the concrete; (c) smoothing of the mitered surface-edge.

3.2.4. *Green post-processing:*

After initial curing of the concrete, the long edges of the elements were post-processed in order to create a dry joint. For this, a steel disc with a diameter of 200 cm was mounted to the spindle of the milling head. With a rotation of 200 rpm and a feedrate of 3000 mm/min, the edges were first cut to miter (Figure 5b), the excess material was removed, and the edge was subsequently smoothed in a second pass (Figure 5c).

3.2.5. *Assembly:*

After curing for two days the planar elements were detached from the wooden baseplate by laterally moving them. Due to the low weight of each element of merely 60 kg, the elements were lifted into place by only two persons (Figure 6).

(a) (b) (c)

Figure 6. Assembling process of one module: (a) assembly with three people; (b) as-sembled element; (c) positioning using a crane.

4. Results and Reflections

The experiment resulted in a 2.2 x 1.5 x 1m prototype, which is part of the larger structure depicted in Figure 4. The prototype was fabricated in 25 minutes excluding waiting time, whereas the spraying process took 12 minutes and post-processing lasted 8 minutes. Assembling of the module consumed another 5 minutes. During the fabrication process, the following observations were made: Spraying resulted in good compaction, was fast and offered consistent height control. However, the starting and stopping procedures of the spraying process are not yet precisely controlled, requiring to extend the starting and ending point of the contour. With regards to the reinforcement, it became apparent, that using pre-cut strips of carbon fiber mats is an effective measure to reduce the structural thickness of the elements. However, the manual placement did not prove to be not sufficiently precise, causing collision conflicts during the cutting of the edges during post-processing. The subtractive post-processing of the green concrete is a novel approach in itself. It proved to be fast and with little energy consumption compared to cutting cured concrete. Moreover, it proved to be sufficiently precise at least for wet joining techniques using a thin bed of mortar. However, for force-locking dry joints, the precision should be improved. Due to the low weight of the components, the assembly was possible with only three persons. As no connection mechanisms were integrated in this first prototype, lashing belts were used to connect the components.

5. Conclusions and future work

This initial prototype represents the first proof of concept for a just starting research project. Yet, it already demonstrates a high potential for efficiently fabricating lightweight loadbearing 3D printed spatial structural systems in reinforced concrete. However, in order to realize the full potential of this method and make it applicable for largescale, free spanning constructions, further investigations have to address the following aspects: At this stage, the computational workflow starts by rationalizing any given, arbitrary surface. This will be further developed to also cover the automated, computational generation of a structurally informed surface geometry. Moreover, the current module design is still at its most basic stage. As such, the modules have to be developed further specifically in two regards: Firstly, in respect to the overall typology, and secondly, regarding their functional integration. The former concerns, for example, the load transfer in both directions, longitudinally as well as laterally. Here the key challenge will be the development of more sophisticated module typologies, allowing for improved connectivity and multidirectional load transfer between neighboring modules. The latter concerns the automated integration of functional features, as for example interlocking mechanisms like finger joints, the incorporation of pre-stressing tubes and structural reinforcement, as well as the integration of precast couplers in order to structurally connect the elements on the component level, as well as on module level. Accordingly, additional fabrication steps, including, rebar cutting, tube bending, as well as pick and place processes for the precise placement of the precast couplers will be implemented into the overall fabrication process. Additionally, strategies for an automated assembly of the components into modules will be explored in further research. In the next phase of the research, the goal is to realize larger spatial structures consisting of several modules and use those to perform a structural test. Only in that way the overall performance, ranging from design and fabrication to assembly logistics and structural efficiency can be evaluated and compared to current standards in the fabrication of spatial structures. In summary, the examples of Nervi´s aircraft hangars are early demonstrations, how the modularization of spatial structures into planar components can yield in highly material, fabrication, and structurally efficient constructions. Against the background of new design and calculation tools, new production technology as well as new materials, it becomes evident that these developments today dramatically widen up the design space of this approach.

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