Formwork-free, continuous production of variable frame elements for modular shell structures

Egor Ivaniuk, M.Sc., Prof. Dr.-Ing. Viktor Mechtcherine
Institut für Baustoffe der TU Dresden, 01062 Dresden
E-Mail: egor.ivaniuk@tu-dresden.de, Telefon: +49 351 463 42851

Summary

Conventional construction of concrete shells involves a costly and time-consuming erection of custom formwork. An alternative approach that avoids this is an on-site assembly of shells from prefabricated modules. This article presents a new, highly automated method for the production of such modules. The proposed method combines the technology of full-width 3D concrete printing using strain-hardening cement-based composite and the technology of robotic textile mesh production from mineral-impregnated carbon yarns.

1 Introduction

Concrete shell structures are highly effective in load-bearing, which is why they require considerably less material in comparison to other types of structures used in concrete construction. Nevertheless, concrete shells have never gained much popularity. The main reason behind this is the use of a very time-consuming and labor-intensive traditional casting method, which requires both highly skilled labor and complex and therefore expensive formwork. The reuse of this formwork is seldom possible, which usually leads to a large amount of waste [1], [2].

To tackle this challenge, several alternative methods have been proposed over the years, including the use of flexible membranes, pneumatic formwork, and pneumatic forming of hardened concrete [3]. Nearly all these approaches are, however, either geometrically too imprecise or limited in available geometries. An exception are approaches based on the assembly of shell structures from prefabricated modules; see e.g. Figure 1. The project "Adaptive Concrete Diamond Construction (ACDC)" being developed at the TU Dresden aims to create a method for highly automated and economically feasible production of shell structure modules. Additionally, the project pays special attention to the high mechanical robustness of edges and to the reinforcement of the modules.

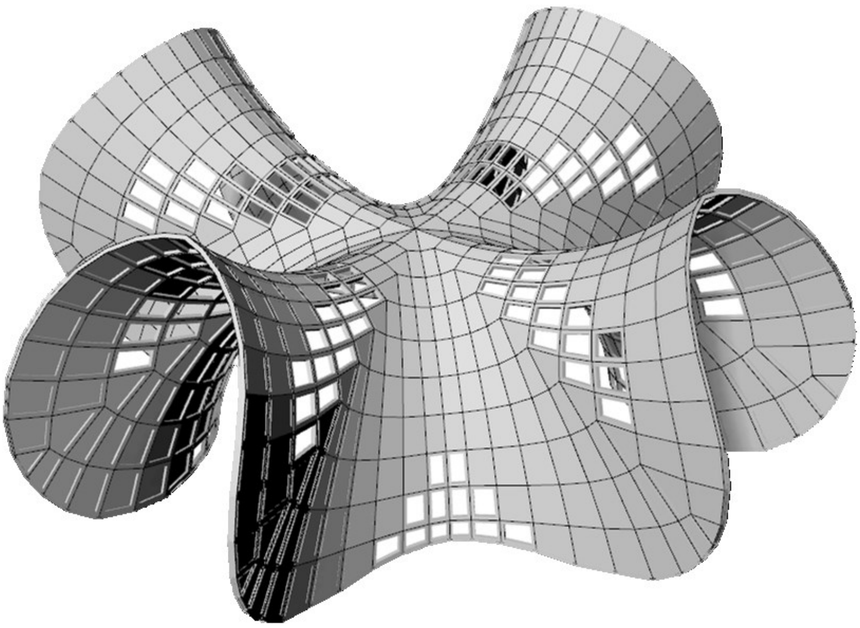


Figure 1 A design of a concrete shell structure assembled from planar prefabricated modules. Drawing: Zlata Tošić, TU Dresden, Research Group Geometric Modeling and Visualization

2 Module production

The proposed method for module production consists of five sub-processes according to Figure 2:

1) 3D printing of the first layer of the module contour, which subsequently serves as integrated formwork;
2) Filling the first layer of the module contour with concrete;
3) Reinforcing the module with carbon textile mesh;
4) Printing the second layer of the module contour;
5) Filling the second layer of the contour with concrete.

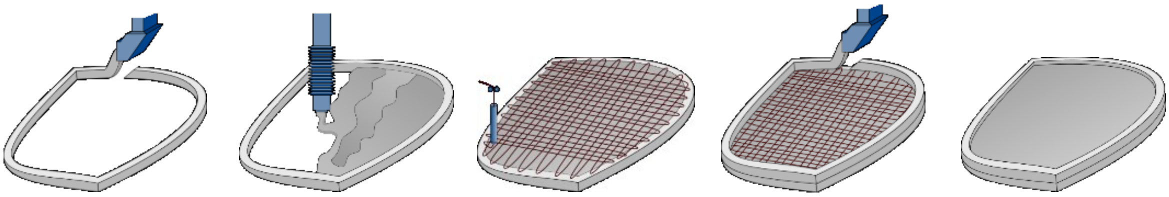


Figure 2 Fabrication steps in the automated flow production of modules. Drawings: Michaela Reichardt, TU Dresden, Institute of Construction Materials

In steps 2 and 5, filling with concrete can be performed by pumping, pouring, or spraying, depending on the concrete type in use and the available machinery. It is also possible to produce frame modules, i.e., the modules without infill, as was already demonstrated earlier [4]. For this, steps 2 and 5 need to be skipped. Since the technologies for filling shallow horizontal molds with concrete are well established already, the focus of the research at hand is on 3D printing of the contours as well as on laying reinforcement.

In steps 1 and 4, the positioning of a printer is computer-controlled and fully automated. The geometric freedom provided by 3D printing technology enables the creation of modules of any shape without the need for formwork; see Figure 3a. To assemble double-curved shell structures from planar modules, the side faces of the modules must have a certain slope, most often different for each face. This can be achieved by equipping a nozzle of a 3D printer with computer-controlled rotating trowels; see Figure 3b. An alternative approach is to post-process the printed module using milling or grinding. This would allow achieving higher accuracy in the manufacture of modules, however, it also would likely lead to an increase in the production time and the generation of waste.

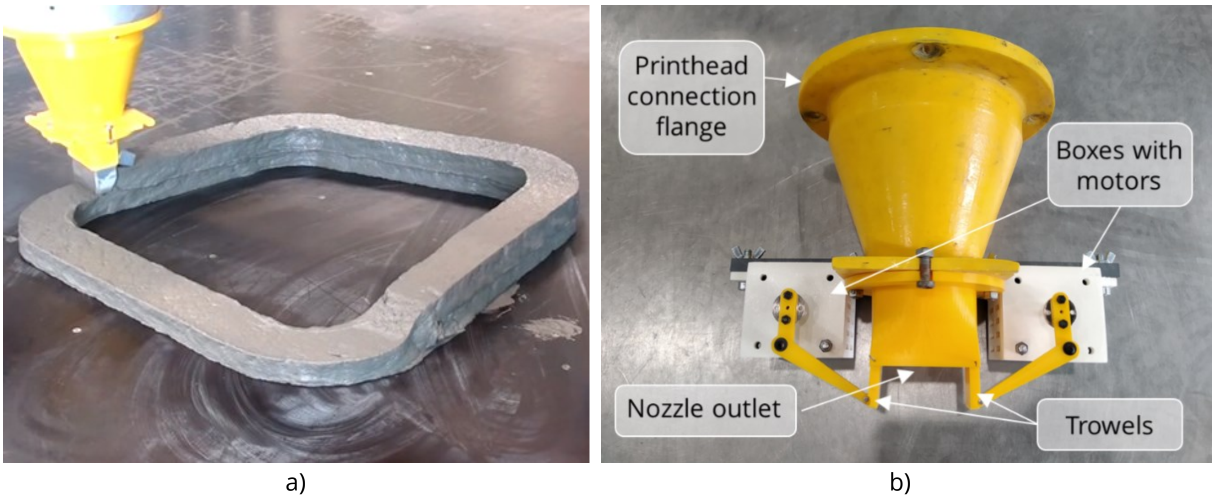
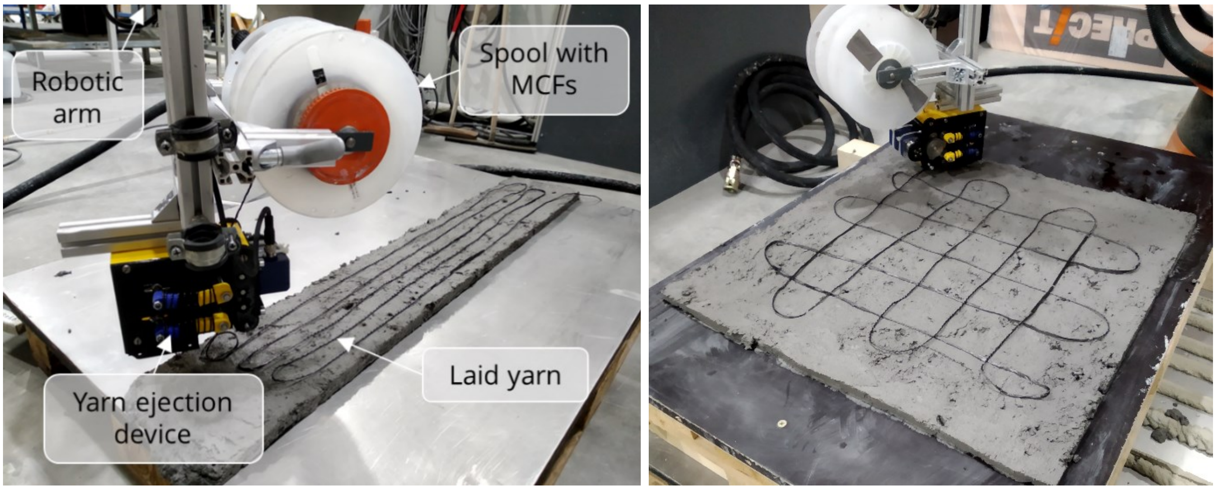


Figure 3 a) 3D printing of a module contour and b) nozzle equipped with trowels with adjustable inclination. Photos: Egor Ivaniuk

Textile mesh, placed in step 3, serves not only as reinforcement, but also provides an additional bond between the outer edge and the infill. Reinforcement can be either cut from the prefabricated mesh or custom produced by laying a mineral-impregnated carbon-fiber composite (MCF) using a robotic arm [5]. While the use of prefabricated textile mesh as reinforcement is a straightforward, easy-to-implement approach, it has two drawbacks. First, cutting irregular pieces of textile reinforcement out of prefabricated mesh causes a considerable share of waste material. Second, the use of prefab reduces the flexibility of the entire technology. Therefore, the focus has been on developing an approach for automated in situ fabrication of reinforcement using carbon yarn, inline-impregnated with a mineral suspension. For this purpose, a special device for the controlled application of carbon yarn was developed and attached to a robotic arm; see Figure 4a. The movement of the robotic arm at the point of yarn ejection is monitored in real-time, in this way enabling the process control, since the length of the yarn ejected exactly corresponds to the traveled distance of the ejection point. Figure 4b shows an example of reinforcement mesh produced using such robotic laying of carbon yarns. This technology can also be applied to reinforce module frame too, if necessary. In this case, the yarn can be laid along the edge of the module in step 3.



a) b)

Figure 4 a) System for freeform robotic laying of mineral-impregnated carbon-fiber composites (MCFs) and b) MCF laid in a grid pattern. Photos: Egor Ivaniuk

Since each of the steps can be done using robots, the entire module manufacturing process can be fully automated. The proposed technology does not require any pauses between the steps, which allows the modules to be produced quickly and economically viable due to the short downtime of equipment. A conveyor system can be implemented for the mass production, in which a platform with a module moves from one station to another, where all production steps are performed sequentially. Eventually, the platform with the completed module is transported to a storage room for concrete curing.

3 Materials

Strain Hardening Cementitious Composite (SHCC) is the material used for 3D printing the contour of modules [6]. This material, reinforced with short fibers, was chosen because of its capability to withstand not only high quasi-static compressive and tensile forces, including concentrated forces at the contact areas with other modules, but also dynamic forces acting during transportation and assembly. Developed printable SHCC exhibited a compressive strength of over 80 MPa and withstood tensile stresses exceeding 4 MPa showing a quasi-ductile behaviour in case of overloading [7]. In addition to very high mechanical performance, SHCC yielded all the characteristics required for 3D printing, namely, a long open time, high water retention capacity, pumpability, extrudability, shape stability after deposition, and high quality of the printed surface.

The choice of carbon textile as the material for module reinforcement is based on its high tensile strength and excellent durability [8]. The latter property enables a reduction of the concrete cover to merely a few millimeters, thus, allowing the production of very thin structures. To produce custom reinforcement using developed technology for robotic freeform yarn laying, the carbon yarn need to be coated with a mineral micro-suspension shortly before its deposition. Previous studies showed that such coating considerably enhances the bond between yarn and concrete matrix as well as the mechanical performance of the reinforced elements at elevated temperatures [9].

4 Conclusion

The authors suggested a new, fully automated method for the in-line production of modules for shell structures. The method utilizes and combines the technology of 3D concrete (here: SHCC) printing and robotic freeform laying of mineral-impregnated carbon yarns. The next planned stage of the project "Adaptive Concrete Diamond Construction (ACDC)" is to construct a modular shell structure consisting of modules with and without filling in order to demonstrate the feasibility of the new technology.

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