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Design and Fabrication of a Non-standard, Structural Concrete Column using Eggshell: Ultra-thin, 3D Printed Formwork

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Abstract. This paper describes the design and fabrication process of a concrete column cast in ultra-thin, 3D printed formwork, using a process known as Eggshell. The column was prefabricated as part of a real-world construction project, serving as the main load-bearing element for a reciprocal timber frame structure. The fabrication of the column required upscaling of the Eggshell process, to allow for the fabrication of elements of an architectural scale. Furthermore, several challenges had to be addressed such as: integration of reinforcement, establishing the formwork design space, and scaling up the 3D printing process. For the production of the final column a 1.5 mm thin formwork was 3D printed, after which it was combined with a prefabricated reinforcement cage and filled with concrete in a set-on-demand casting process. The successful realization of the project provides a first example of a full-scale building element produced with the Eggshell fabrication process. By 3D printing the formwork, geometrical freedom in concrete construction is greatly expanded, as well as formwork waste reduced.

Keywords: 3D printing, formwork, digital concrete, robotic fabrication, set-on-demand concrete, reinforcement

1 Introduction

Formwork is an essential element in construction of concrete building components, holding freshly poured concrete in place until it reaches its final, hardened shape. The shape of the formwork ultimately determines the geometry of the concrete and this is – along with material properties and reinforcement – what determines structural performance. Research shows that by optimizing concrete geometry, it is possible to achieve material savings of up to 70% compared to a standard concrete building component [1]. These types of optimized building components, however, are expensive to fabricate, mainly due to the difficulty of constructing the formwork [2]. This is one of the reasons complex, non-standard concrete structures remain uncommon. However, with cement production being responsible for 8% of global anthropogenic CO_2 emissions [3] it is imperative that material-efficiency is considered a key driver in the construction process. In order to make concrete construction sustainable, more efficient ways of formwork fabrication therefore have to be developed.

Digital fabrication presents a potential solution for this problem and various innovative formwork fabrication processes have been developed. Subtractive processes such as computer numerically controlled (CNC) milling of wood [4], foam [5], ice [6] and wax [7] enable precision-manufactured formwork, however, they are often wasteful and time-consuming. Adaptive processes such as Smart Dynamic Casting [8] (SDC) or flexible mould techniques [9, 10] produce no waste but instead impose limitations in the type of geometry that can be produced [11].

Lastly, additive manufacturing processes offer a relatively wide range of geometric possibilities. Binder jetting [12] especially has high geometric flexibility, although the formwork material cannot be recycled, making it a resource-intensive process. Fused deposition modelling (FDM) 3D printing offers potential for formwork recycling as well as geometric freedom. However, FDM produces fragile structures that need some form of support to resist the hydrostatic pressure exerted by the fresh concrete. This can be done using counter pressure casting [13] or a printed external scaffolding [14]. Counter pressure casting, however, increases complexity when casting and an external printed scaffolding greatly increases printing time.

In contrast to these approaches is the fabrication method Eggshell [15], the subject of this paper. Eggshell enables the use of FDM 3D printing of ultra-thin formworks with a high degree of complexity, good surface quality and no additional support. The key enabler of this fabrication process is a set-on-demand Digital Casting (DC) approach, first developed during the SDC project. DC allows for controlled hydration of the concrete, resulting in only a limited amount of lateral pressure exerted on to the formwork.

This paper describes the challenges that emerged in the design and fabrication process of a non-standard, structural, full-scale concrete column using Eggshell. Eggshell presents a novel fabrication system, which until recently had only been explored for the fabrication of smaller scale elements with a high degree of complexity. Thus, the main challenge lies in scaling up the process for the fabrication of full-scale building components. The first step of bringing this technology into an architectural scale was done with the project: Future Tree, built for the Swiss engineering firm Basler & Hofmann [16, 17].

2 Fabrication concept and setup

2.1 Fabrication concept: Consecutive fabrication

The Eggshell fabrication process leverages on a fast setting set-on-demand concrete that is digitally cast into an ultra-thin, 3D printed formwork. The process aims to 3D print the formwork and cast concrete *simultaneously*, enabling the production of highly complex structures. This concept has been successfully demonstrated with prototypes up to 1.60 m tall [18]. However, scaling this process up to a building scale introduced two major challenges: slow printing speed in comparison to the filling rate of the fast-setting concrete and the inclusion of reinforcement compliant to building codes. The experiments presented in this paper, therefore, make use of a *consecutive* fabrication process as illustrated in Fig. 1. In this process a formwork is 3D printed (1) after which it is combined with a reinforcement cage (2) and filled with a set-on-demand concrete (3). One advantage of this process is that the filling rate (vertical speed at which concrete is cast) does not have to be synchronized with the printing rate (vertical speed at which the formwork is printed), see Fig. 2b.

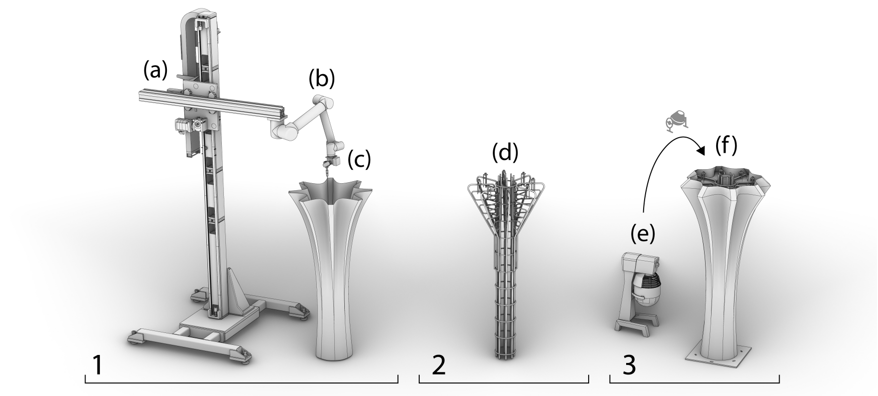


Fig. 1. The consecutive fabrication process and setup.

However, consecutive fabrication is only suitable for the production of elements with a relatively simple geometry, because of two major limitations:

1. As concrete has to be fed in from the top, the bottom of the formwork has to be accessible for casting. If the bottom is not accessible, cast concrete will deposit on the walls of the formwork, causing uneven hydration, poor surface quality, cold joints and possible blockage (see Fig. 2b).
2. A prefabricated reinforcement cage cannot always be fitted inside of the formwork, especially in the case of a complex formwork with high curvature (see Section 3.1).

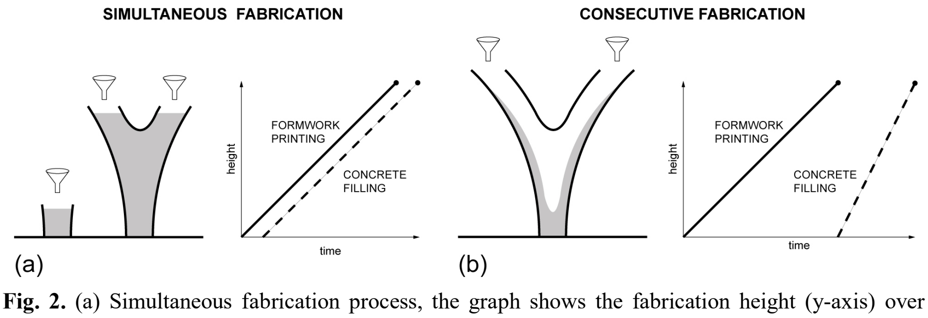


Fig. 2. (a) Simultaneous fabrication process, the graph shows the fabrication height (y-axis) over time (x-axis). As the slope of the two graphs of printing and casting is the same, the printing rate is equal to the filling rate (b) Consecutive fabrication process: Slope of concrete filling is higher than the formwork printing process, meaning a faster filling rate than printing rate.

2.2 Fabrication setup

The fabrication setup (Fig. 1) consists of a Universal Robots UR10 six-axis robotic arm (b) mounted to a Siemens vertical linear axis (a). Attached to the robotic arm is a custom-made filament extruder (c), which uses 2.85 mm Polyethylene Terephthalate Glycol (PET-G) filament and has a maximum flow rate of 0.35 kg/h. The total build volume of the setup is 1.2 x 1.2 x 3.6 m^3 (width, length, height).

The material mix and acceleration system are inherited from the SDC project [19]. In the process a large batch of concrete is prepared with a retarder, ensuring its workability for up to eight hours. Smaller batches of concrete are then taken and mixed with an accelerator in a planetary mixer (e), after which the accelerated batches are cast into the formwork (f). The main mix design has been slightly adapted from [19] in order to include polypropylene fibres. The W/B ratio was kept the same but the proportion of admixtures was slightly adapted to accommodate the change of rheology brought by the fibres, and the fact that the concrete needed less retardation time. This led to increase the superplasticizer content but decrease the sucrose content. The accelerator content was also restricted, for durability concerns, to the amount advised by the manufacturer of 4 wt% per cement content. Several slightly different material mixes were used throughout the development phase (Section 4.2), some including aggregates up to 8 mm and some with aggregates up to 4 mm (such as the final mix design used). Several of the material mixes used therefore technically classify as a mortar but for the sake of simplicity, all are referred to as a concrete.

3 Challenges

3.1 Integration of reinforcement

The Future Tree column is a structural building element onto which a reciprocal timber frame of 100 m^2 is placed [16]. This results in a pavilion situated in an outside courtyard on the premises of Basler & Hofmann in Esslingen, Switzerland. Due to public access to the pavilion the structure had to ensure building code compliance. Therefore, despite the fact that several novel reinforcement concepts exist for the Eggshell process (active reinforcement, steel hooked fibres [15]) it was chosen to use conventional, passive reinforcement. A benefit of the Eggshell fabrication process is that it allows for the relatively easy integration of such reinforcement: a reinforcement cage can be prefabricated and installed inside the thin formwork. Still, it is not possible to combine every reinforcement cage with its formwork, especially as geometric complexity increases (Fig. 3a). Splitting the reinforcement into several parts could provide a solution, however at a cost of fabrication tolerance. The design of the column was therefore adapted to allow a single reinforcement cage to be placed in from the top (Fig. 3b).

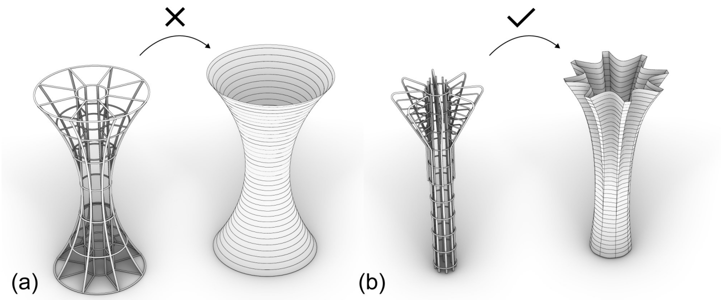


Fig. 3. (a) A combination of reinforcement and formwork geometry that cannot be combined. (b) Reinforcement can be placed inside the formwork from top.

The reinforcement cage was designed to closely follow the column geometry. The reinforcement in the core of the column was dimensioned to resist the global loads of the timber roof, while minimum reinforcement was disposed in each of the column's eight ribs. A small concrete cover (28 mm) results in the ribs since they are very thin (70 mm at the thinnest point). Therefore, the reinforcement had to be fabricated to a tolerance of 10 mm – which proved to be very challenging for the manufacturer – and stainless reinforcing steel was used to avoid corrosion issues. The maximum concrete cover was set to be within limits of international building code recommendations.

3.2 Formwork design space

This section discusses two sets of experiments: (1) maximum overhang that can be fabricated with Eggshell and (2) effect of formwork geometry on the concrete casting process. These experiments were necessary in order to determine the final geometry of the Future Tree column.

Materials and methods. In both experiments, 3D printed formworks were filled with the set-on-demand concrete (Section 2.2) to observe the point of breakage. Relevant parameters are the geometry of the formworks, as well as the filling rate (vertical casting rate in mm/min) and the 'setting time' (considered here as the time in minutes after which the concrete can sustain its own weight and is therefore not exerting lateral pressure onto the formwork under our normal operation conditions). This time roughly corresponds to the onset of the acceleration period. The maximum pressure can be calculated using the equation for hydrostatic pressure Eq (1).

$$P = \rho \times \mathrm{g} \times \mathrm{h} \quad (1)$$

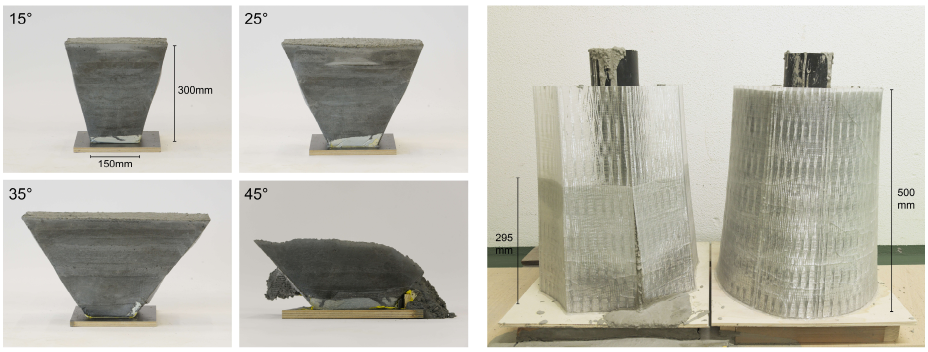
Within each set of experiments, the vertical filling rate and setting time are the same, and therefore so is the evolution of the hydrostatic pressure acting on the formwork. However, as geometry and surface to volume ratio of the formwork changes, breakage behaviour most likely also changes.

Experiment 1: Overhang. Four formworks were 3D printed with an overhang of 15°, 25°, 35° and 45°. Through penetrometer measurements [20] it was determined that setting time was 50 minutes after acceleration and casing. Assuming a filling rate of 2 mm/min this gives a maximum of 100 mm of concrete that is exerting pressure on the formwork. Filling in the values in Eq. (1) for a material density of 2300 kg/m^3, acceleration of gravity of 9.81 m/s^2 and height of 0.1 m gives a maximum pressure of 2.26 kN/m^2. The results of the first experiment (Fig. 4a) show that the formworks with an overhang of 15 - 35° could be fabricated successfully, however, the 45° formwork failed after 50 minutes of casting, equalling to a pressure of 2.26 kN/m^2.

Experiment 2: Geometry. Secondly, breakage behaviour was studied for formworks with a different cross-section. Two design options, one with a circular shape and another octagonal with convex edges were 3D printed in a 1:1 scale (Fig. 4b). It was expected the formworks could sustain a filling rate of 5 mm/min. Two iterations of the experiment were completed. Both iterations showed that the circular formwork was able to be fully filled with concrete, whereas the octagonal formwork broke at 290 mm of concrete height in the first test and 300 mm in the second. This gives an average breaking height of 295 mm, equalling to 6.66 kN/m^2 using Eq. (1). In both cases breakage occurred in one of the ribs, with a vertical crack starting at the bottom of the formwork.

Conclusion. These tests are only a first insight into the design space of Eggshell, meant to provide some guidelines for the Future Tree design. Indeed, the results are not conclusive and further work will focus on systematic tests to fully quantify the limitations of the system, as breakage behaviour is not yet understood well. However, some design guidelines could be determined:

1. Experiment 1 showed that an overhang of 35° could be fabricated without problems and this was therefore set as the maximum design angle.
2. Experiment 2 showed that the circular formwork was able to sustain a higher amount of pressure and could therefore be filled using a faster filling rate. As one of the aims was to reduce the total casting time, it was therefore decided to adjust the design to the circular cross-section in the bottom.



(a) (b)

Fig. 4. (a) Overhang experiments, showing breakage in the 45° model. (b) Geometry tests, breakage occurred in the polygonal shaped formwork (left) whereas no breakage occurred in the circular shaped formwork (right).

3.3 Large scale 3D printing

Due to the relatively large dimensions of the column (a top diameter of 1 m) it proved challenging to 3D print the thin formwork. For prints with a diameter exceeding 0.7 m, severe issues of layer delamination were found. These issues can be explained by deformations due to shrinkage of the printed material, a common problem in 3D printing [21]. Shrinkage was further amplified as the Eggshell print setup is situated in a large hall with sub-optimal printing conditions (low ambient temperature). A solution could be a heated chamber around the printing setup, however, this was deemed unfeasible due to the large dimensions of the setup. Alternatively, a series of experiments was conducted, aiming to define the threshold of when delamination would occur. Several sets of experiments were conducted in which a circle of 1 m in diameter was printed up to a height of 50 mm with a constant speed of 45 mm/s [15]. The only changing variable in between tests was a zigzag pattern that was applied to the geometry. By dividing the circular geometry into points and shifting these points in- and outwards, a series of concave polygons was created. The experiments allowed to conclude that layer delamination could be prevented by limiting the length of a straight edge to a maximum of 70 mm. This fabrication- and material constraint was turned into a design parameter, that was used to design the final formwork texture (Fig. 7b).

4 Design and fabrication

4.1 Design

As the column had to support the timber roof structure the starting point of the design was the eight timber beams at the bottom of the roof. The timber beams connect to the column through eight vertical 'ribs'. Between these ribs, material was removed in order to reduce the amount of concrete used in the column.

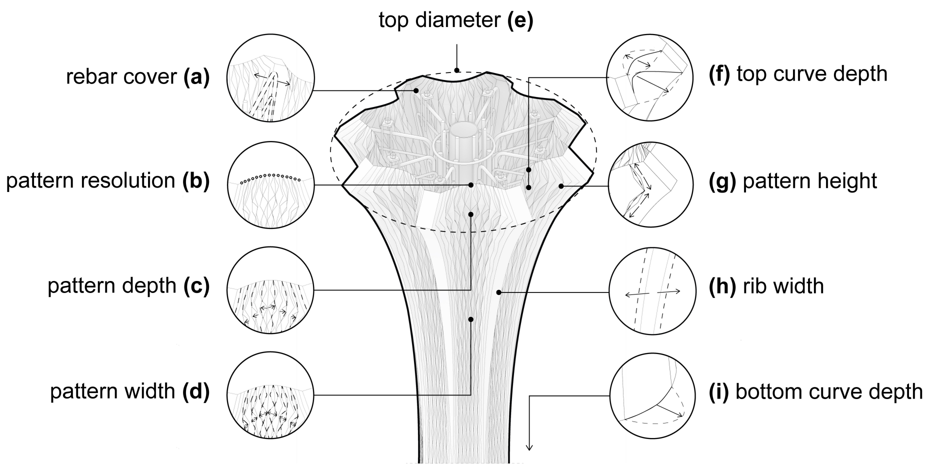


Fig. 5. Design parameters.

The column was designed using McNeel Rhinoceros 3D, Grasshopper 3D, as well as through custom Python scripts. A parametric model (Fig. 5) was generated that allowed for easy manipulation of the column design. The design could be changed based on the results of the experiments conducted such as: overhang (Fig. 5e), pattern geometry (Fig. 5b, c, d, g), shape of the cross-section (Fig. 5f, j) and reinforcement cover distance (Fig. 5a). This allowed for constant modification of the design based on new findings. Finally, the parametric model could also be used to directly generate the fabrication data, eliminating the need of an additional step of slicing the geometry.

4.2 Fabrication

In order to determine the constraints of the full Eggshell process in a large scale, it was necessary to conduct a series of 1:1 experiments. Three full-scale column prototypes were therefore fabricated and with each prototype, different improvements were made, as well as new problems encountered (Table 1). A material mix with aggregates up to 8 mm was used for Prototype 1 and 2, whereas for Prototype 3 and 4 a material mix with aggregates up to 4 mm was used.

Table 1. Overview of problems and improvements in the different prototypes.

Prototype	Improvements made	Problems encountered
#1 (Fig. 6a)	-	- Unpredictable concrete behaviour due to changing ambient conditions.
#2 (Fig. 6b)	- Material testing during fabrication (flow diameter and penetrometer).	- Reinforcement not made to tolerance (Section 3.1).
#3 (not shown)	- Reinforcement bent using template.	- Geometry of bottom failure (Section 3.2).
#4 (Fig. 6e)	- Geometry changed.	-

After the knowledge gained from the three prototypes, the fourth and final prototype (Fig. 6e) could successfully be fabricated. The formwork (Fig. 6c) was printed in a fully autonomous, continuous process with a layer height of 1 mm, layer width of 1.5 mm and printing speed of 45 mm/s. Total printing time of the column formwork was 26 hours with a toolpath length of just over 4 km.

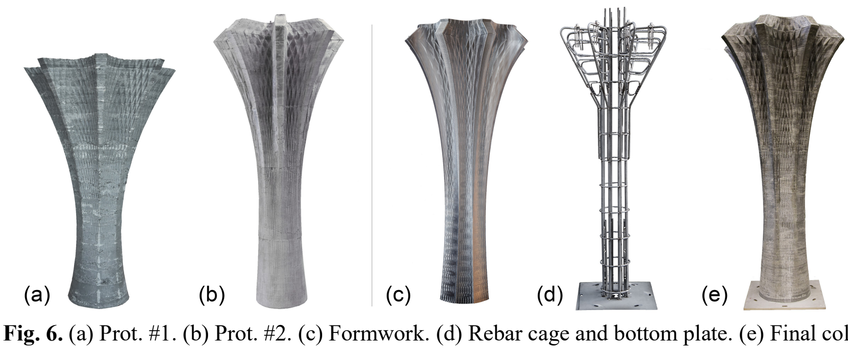


Fig. 6. (a) Prot. #1. (b) Prot. #2. (c) Formwork. (d) Rebar cage and bottom plate. (e) Final column.

The reinforcement (Fig. 6d) was then lifted in and the formwork precisely aligned with the steel base plate using a laser cut wooden template. Eight vertical reinforcement bars with a length of 600 mm had been pre-welded to the base plate, hereby ensuring a proper connection between concrete column and base plate by fully encasing the vertical bars. An additional laser cut wooden plate was placed around the column at a height of 2 m, in order to ensure deviation at the connection point would not exceed 5 mm. Subsequently the formwork was filled with the set-on-demand concrete over a period of eight hours. Total volume of the column was 270 L and the filling rate was varied over the height, starting with a high filling rate (6 mm/min) at the bottom and resulting in a lower filling rate (2 mm/min) at the top of the column. Filling rate at the top of the column had to be lower for two reasons: 1) higher overhang resulting in weaker bond between printed layers, 2) the larger size meant a lower surface to volume ratio, resulting in higher stresses on the formwork. After casting, the column was covered and left to cure for 14 days. The formwork was then removed by making a vertical seam with a heat-gun and stripping the column using pliers. Finally, the column was transported to site and connected with the foundation. The timber roof was then added on top of the column in five prefabricated modules.

5 Discussion and Conclusion

The successful fabrication of the column as presented in this paper is a milestone for this research, bringing it from a prototype in a laboratory to a full-scale, structural building component. It shows that FDM 3D printing of formwork in combination with digital casting is a viable strategy for fabricating architectural-scale components. The final formwork for the column weighed just 8 kg, around one hundredth of the weight of the finished concrete column including reinforcement. There are however several key aspects in which further research is necessary:

1) It proved very challenging to integrate the reinforcement cage with the necessary tolerance. Although the 3D printed formwork can be manufactured to millimetre-tolerance, current reinforcement techniques are still unable to produce complex reinforcement with high precision.
2) The aim of the Eggshell research project is to fabricate complex concrete structures in a *simultaneous* process of printing and casting. For this to be viable for large-scale fabrication, current 3D printing tools have to be improved to allow for higher output and ultimately, faster printing.
3) Utilizing 3D printed formwork has the potential to be a fully circular process, as removed formwork can be cleaned, shredded and extruded into new material. This, however, has not been verified but is currently under investigation.
4) The processes concerning stresses in the formwork as a result of concrete hydrostatic pressure are not yet fully understood for non-standard shapes so that more work is required on this front, both theoretical and experimental.

5) Although design efforts were made to reduce concrete in the column, no sophisticated optimisation processes were used. There is however great potential for such methods and this will be further explored in future work.

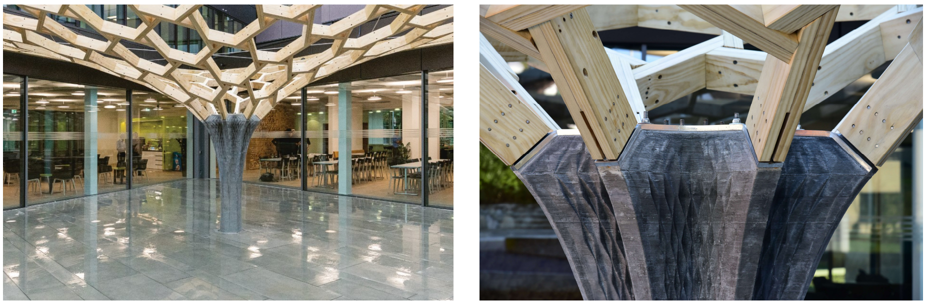


Fig. 7. a) Column placed on site (Image: Basler & Hofmann AG, Stefan Kubli). b) Close-up of top.

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