# 3D Printed Concrete Tectonics

## Assembly Typologies for Dry Joints


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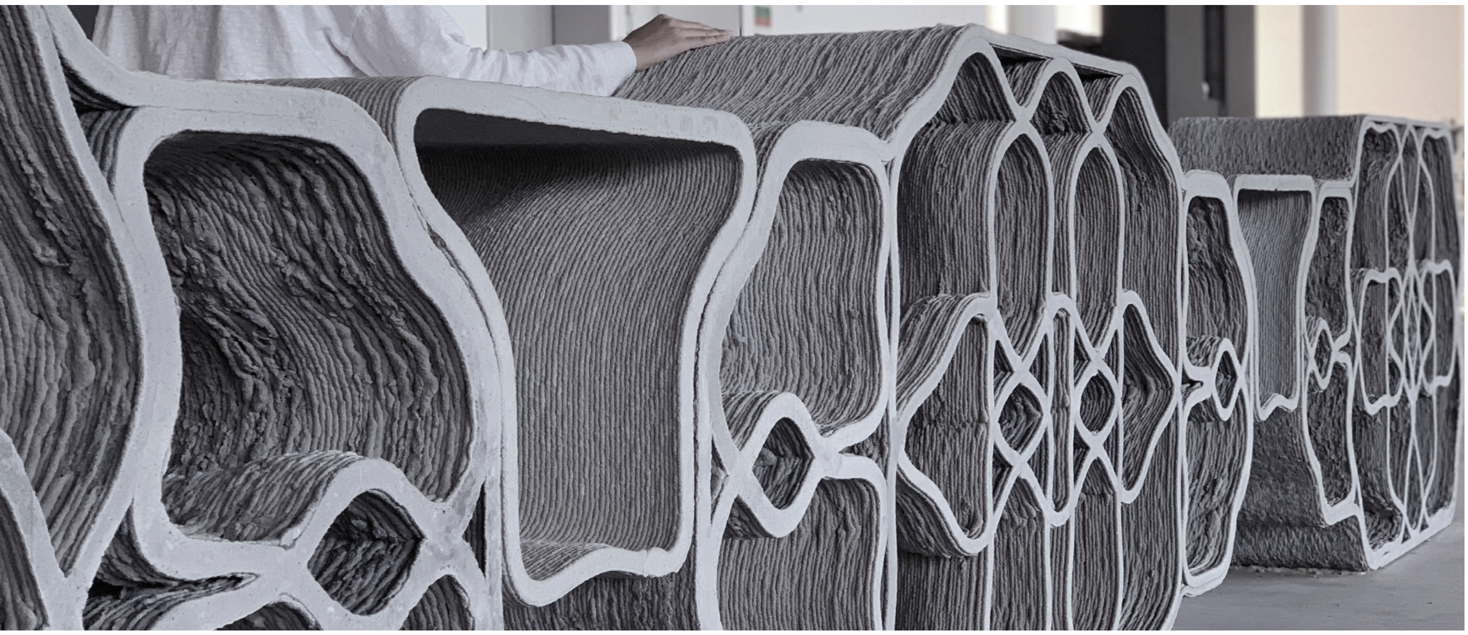

1 Close-up of assembled 3D-printed concrete components


## ABSTRACT

Digital fabrication technologies and additive manufacturing techniques opened new opportunities and new challenges for the construction industry. Particularly, Concrete Extrusion 3D Printing (CE3DP) introduces valuable opportunities for large-scale architectural elements. However, segmentation and assembly strategies have not been developed, and it remains a limiting factor for the expansion of concrete 3D printing to an industrial scale.

In this context, the present research focuses on the design and fabrication possibilities of assembly interfaces, an essential topic for scaled-up 3D-printed concrete components. Therefore, dry assembly interfaces in different printing orientations are prototyped to investigate characteristics and limitations of connection options.

## 3D PRINTED CONCRETE TECTONICS

### Introduction

Concrete Extrusion 3D Printing (CE3DP) can be defined as the process of joining the deposited concrete layer upon layer to create pre-designed objects from digital data. The emergence of CE3DP technology introduces new possibilities to the construction field and changes the paradigm of how architects can conceptualize, design, and build. However, the collective body of assembling such elements had so far been limited due to fabrication constraints specific to CE3DP. This paper describes a research project with the primary goal of exploring the tectonics of dry joints in 3D concrete printing in light of specific fabrication and design parameters.

The architectural term tectonics is described as the art of joining (Frampton et al. 2007). It refers not just to the activity of making the materially requisite construction that answers certain needs but rather to the activity that raises this construction to an art form (Maulden 1986). Today, tectonics is taking on another dimension with the rise of advanced digital fabrication techniques. With the introduction of CE3DP in architectural practice, a quest to redefine new tectonic expression starts (Wolfs and Salet 2016).

### State of the Art

Recently, several bridges have explored potential opportunities and challenges with 3D-printed concrete tectonics (Salet et al. 2018). One of the latest 3D-printed concrete projects is the topology optimized prestressed 3D-printed concrete where the concrete segments (Figure 3) were brought together through the planar interface of each end (Valdivieso 2019; Vantyghem et al. 2020). The same assembly method was applied in the Baoshan pedestrian bridge project (Figure 4) (Xu et al. 2020). Both bridges underline the current state of the art with regards to the assembly strategy of 3D-printed components, where the assembly interfaces are commonly planar because of printing on a flat surface.

Another assembly approach was joining 3D-printed components at the surface's sides. This approach provided noticeable geometrical freedom at the interfaces as it's not confined to the planarity of the printing substrate. An example of this can be seen in the 3D-printed double-curved concrete shell structure (Figure 5) (Schipper et al. 2017). The printed segments inherited the surface geometry of the supporting double-curved mold, which allowed for an intricate interface to be realized. *Cohesion Pavilion* demonstrates an assembly strategy where the interface between components is informed by the outer geometry (Figure 7) (Grasser et al. 2020). A similar assembly strategy

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2 3D-printed concrete columns, DBT, ETH Zurich (Anton et al. 2020)

3 Flat assembly of 3D-printed concrete components of the Topology optimized bridge (Valdivieso 2019)

4 Flat assembly of 3D-printed concrete components of the Baoshan bridge (Xu et al. 2020)

5 Sideway assembled components of the 3D-printed double-curved concrete shell structure (Schipper et al. 2017)

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6 Sideway assembled components of the 3D printed concrete house (Carra and Stabile 2018)

7 Sideway assembled components of the *Cohesion Pavilion* (Grasser et al. 2020)

was implemented in the 3D printed concrete house (Carra and Stabile 2018), where the 3D printed walls are joined sideways (Figure 6). In the previous examples, an optimized 3D printing process is crucial to achieving controlled surface quality and precise interface for an efficient side-to-side assembly.

To previous work, concrete 3D printing offers more geometrical freedom, and this has led to realizing complex bespoke designs. Nevertheless, assembly logic and connection interfaces of 3D-printed concrete components are still bound to certain limitations of the printing technique, such as the horizontal printing, slicing, and segmentation of elements, printing path, precision, and quality control of surfaces. In this research context, we find potential in rethinking 3D-printed concrete tectonics and developing a new design language of connection interfaces with CE3DP.

## METHODS

The research methodology intertwines the design and fabrication processes. The key elements of the methodology are design research, file to production digital workflow, fabrication set up, prototyping, and a full-scale demonstrator.

### Design Research

The design investigated the existing assembly typologies in concrete 3D printing. Based on the advantages and drawbacks of each strategy, categories of assembly strategies were drawn from the precedent works and the prototypes developed in this research.

### File to Production Digital Workflow

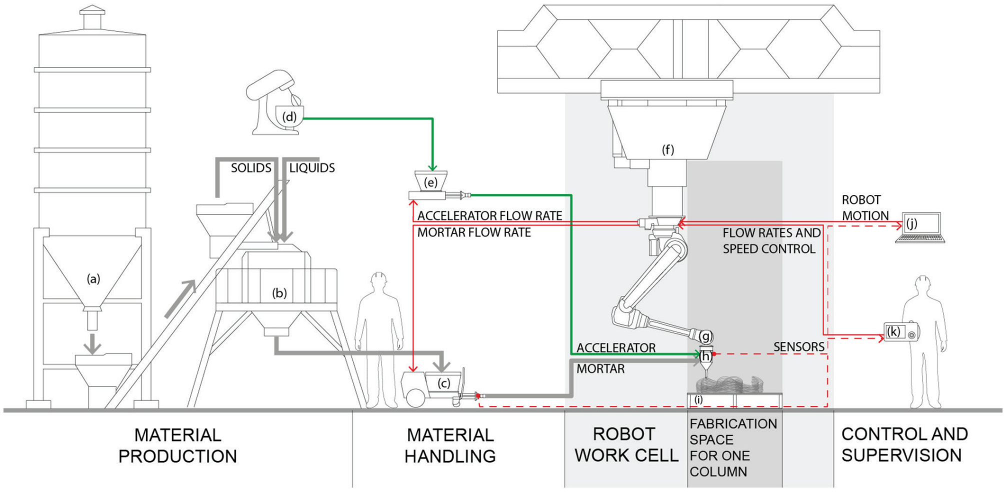
A comprehensive parametric workflow of *design geometry generation*, *geometry validation*, and *analysis* were developed to ensure the printing feasibility of the design geometry according to the material constraints, *3D geometry slicing*, and *printing path generation*. In addition, the digital tools provided data such as printing path length and approximate concrete volume required for material preparation.

### Fabrication Setup

The robotic fabrication setup shown in Figure 8 (Anton et al. 2021) consists of a 6-axis robotic arm on an overhead 3-axis gantry system, concrete pump, accelerator pump, and an online communication station. At the robotic arm end effector, a concrete mixing and extrusion tool is attached with two segregated material inlets, one of which is connected to the concrete pump through a hose while the other inlet receives the accelerating admixture from a small pump via a thin plastic tube. The two components are mixed in the top part of the tool and extruded through through a nozzle of 15mm diameter opening. The two pumps are running continuously during the printing process. As a result, the print path must be continuous and due to the to the low initial yield stress of the filament, the cantilevering freedom is limited. This CE3DP process is described by ETH Zurich researchers (Anton et al. 2021), and the online communication system uses COMPAS-FAB (Rust et al. 2021) and COMPAS-RRC (Fleischmann et al. 2021).

### Prototypes

Full-scale 3D-printed concrete prototypes were fabricated to assess the assembly typology with reference to the fabrication parameters, material behavior and printing tolerance. To set a framework for prototyping, fixed values for design and fabrication parameter, which evolved from previous CE3DP projects were set. For design, the inclination angle of any surface was maintained to a maximum of 15°. As for fabrication, the compositions of both the concrete and accelerator mixtures were fixed, and the speed of the robotic arm was set to 350mm/s. The assembly typologies explored in this research (Figure 9) includes two main interface types. The difference between them is the direction at which the elements join. The

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8 Diagram of the fabrication setup used in the project: (a) dry mix silo; (b) concrete mixer; (c) concrete pump; (d) accelerator mixer; (e) accelerator pump; (f) 3-axis gantry; (g) robot manipulator; (h) extruder tool; (i) work object; (j) computer; (k) teach pendant (Anton et al. 2021)

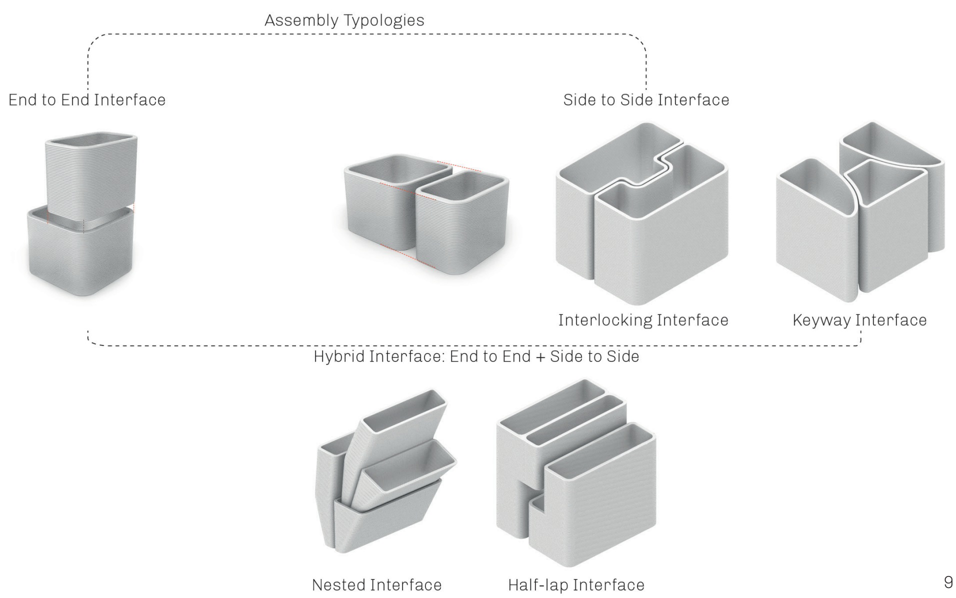
9 Assembly typologies

first interface type is where elements are joined along the normal of the printed layers, throughout the paper, this will be referred to as the End-to-End interface. Inversely, the second interface is where components are connected perpendicularly to the normal of the printed layers, this type is referred to as the Side-to-Side interface. As the nature of the vertical printing process does not allow for non-planar interfaces on both ends of the printed components, a hybrid interface type of End-to-End and Side-to-Side was sought after. This paper addresses side-to-side interfaces and hybrid interfaces.

### Assembly Typologies: Side-to-Side Interface

Interlocking Components—In this approach, the limitations on the geometry of the surface where the interface occurs are very minimal: it can be a planar, single, or double-curved surface. A two-part prototype of a U-shaped interface (Figure 10) was printed to understand the potential of this interface type in terms of fitting accuracy.

Keyway Interface—There are two distinct differences in this subtype from the previous one. First, the number of layers at which the components meet is less. Second, the components touch each other rather than fitting inside one another.

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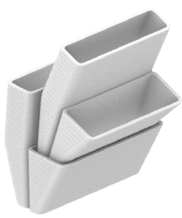

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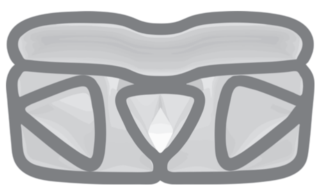

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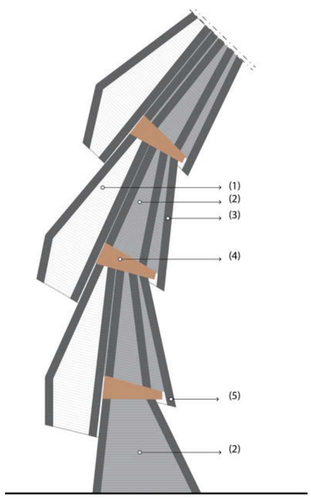


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Results—In the interlocking prototype, it was observed that the provided tolerance gap of 10mm was sufficient for a smooth fitting. In all the experiments the tolerance was determined as half of layer width. However, successful interlocking can only happen in the case of a highly precise print along the entire length of contact surface.

This problem is resolved in the Keyway subtype due to the significant reduction of the contact surface to a small number of printed layers. This increases the probability of having better-fitting printed components. This specific logic can be applied to different geometries while maintaining the technique's advantage.

### Assembly Typologies: Hybrid Interface

Nested Components—Moving gradually towards upscaling, a temporary stand-alone structure of half an arch was designed and broken down to multiple components. The nested approach (Figure 11) emerged as a solution to connect the 3D-printed components in a predefined position through designing one part with a wider cross-section than the other to allow for partial or full nesting. A tolerance gap of 10mm was provided between all assembly faces.

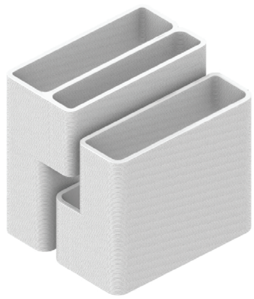
The varying width of the cross-section of each component provides an external surface to conceal the assembly detail, which leads to an overall homogenous reading of the assembled form (Figure 13). Moreover, the function of the internal geometry shown in Figure 12 is performance-oriented. To elaborate, the internal geometry provides a surface for the soft timber wedges, shown in Figure 14. Together, the internal geometry and the timber wedges allow for an adequate load transfer that takes advantage of the great compressive strength of concrete, while reducing the potential tension build up within the nested structure. Moreover, the timber wedges form an inclined plane that is necessary to build up the overall inclination in increments.

Half-lap Interface—The research investigated connecting two components by creating a two-level interface (Figure 15) as a workaround for the technique's limitation of having at least one flat end.

Results—The full-scale assembled Half-Lap prototype shows that the End-to-End interface requires a very accurate printing quality and does not allow for imprecision in the orthogonality, which remains a main repercussion of this fabrication technique. Significant vertical deformation at the end of the two segments can be seen in Figure 16, creating mismatching geometries. Furthermore, as only one interface per element can be printed, it is limited to joining two elements.

### Final Demonstrator

The goal of the final demonstrator, a segmented 3D-printed concrete bar, is to showcase an assembly strategy applied to a design suitable for 3D concrete printing. The bar stretches 7.5 meter in length and 40 centimeters in depth. The bar was segmented to five parts, three long segments



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10 Interlocking prototype

11 Nested components

12 Optimized internal geometry

13 Nested components

14 Diagram section through four 3D printed components of the arch: (1) hollow cavity inside the component; (2) CE3DP porous infill; (3) outer shell section; (4) inclined plane used for assembly; (5) component edge that hides the assembly detail

15 Half-Lap interface

16 Half-Lap prototype

17 Keystone component

of self-intersecting geometry and two connecting keystones (Figure 17). The decision to work with side-to-side connecting interfaces was motivated by the connection aesthetics, segmentation strategy, and printing orientation of the porous structure. During the assembly process (Figure 18), the long segments were rotated 90° to a vertical position and aligned next to one another. Afterwards, the keystones were lowered into place to create a continuous 7.5m surface (Figure 19).

## CONCLUSION

The results of the experiments carried out in this research have shown that various assembly typologies for 3D concrete printed components are possible through investigating design and fabrication parameters that are informed by the 3D printing process. Segmentation and assembly strategies are design-specific and need to be developed together with the printing strategy. For example, choosing a layer orientation different to that of the final position of the printed part extends design and fabrication spaces for CE3DP, especially in prefabrication setups. As explored in the Compound Fabrication project by MIT (Zivkovic and Battaglia 2018), post-processing methods such as 3D scanning and CNC milling could be implemented to create a refined surface quality along the interface which will overcome the local inaccuracies of the printed layers. An enhancement to the fabrication setup could be another approach to address the quality and precision of the printed object. Researchers at ETH Zürich have experimented with printing on a formwork surface instead of a regular planar printing bed (Anton et al. 2020). Furthermore, the research delivers a promising outlook for further development in 3D concrete printed tectonics. While designed as a dry connection, the proposed solutions highlight precision requirements and are applicable to masonry-type connections with the interface materials being mortar for permanent assemblies, or soft materials such as mats or wood wedges (Figure 10) for temporary joining. In addition to compensating some printing inaccuracies, an interface material also reduces local stress concentrations between the elements by distributing the load transfer through the connection to a larger surface, reducing splitting risk. To summarize, there are several approaches to address the imperfections resulting from the fabrication process of concrete 3D printing. These approaches allow for the load transfer between components including permanent assemblies through introducing a mortar-like material that compensates for surface imprecision, post process the superficial area of the printed parts, and use precise formworks during printing in the connection areas.

18 Components assembly process


## ACKNOWLEDGEMENTS

We would like to thank Prof. Dr. Benjamin Dillenburger (Digital Building Technologies) for his support to this work and in particular his continuous guidance for 3D concrete printing research.

Our sincere gratitude goes to Michael Lyrenmann, Philippe Fleischmann, Tobias Hartmann (Robotic Fabrication Lab), Heinz Richner and Andreas Reusser (Concrete Lab) for the technical support in the realization of all the large-scale prototypes.

This research was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement #51NF40-141853). ETH Zürich Foundation supported this research under the project number: 2019-FE-202.


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19 Final demonstrator, 3D-printed concrete bar


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She received her architectural degree, cum laude, in the TU Delft, in 2014 and continued her research until 2016 as part of Hyperbody Research Group. While her scientific research addresses complexity and emergence in architecture, her designs exploit materiality encoded for digital fabrication. Her current thesis, "Tectonics of Concrete Printed Architecture," focuses on robotic concrete extrusion processes for large-scale building components.