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ABSTRACT

Digital fabrication technologies, such as 3D concrete printing, are currently making their way into the construction industry. The primary focus in this field is often on the depositing processes, such as extrusion 3D concrete printing, where material is typically applied in horizontal planar layers. This area has seen substantial progress in recent years. However, numerous research and development projects are specifically targeting the additive manufacturing of unreinforced raw concrete components. When implementing these technologies in practice, it has become clear that additional processes, such as fully automated process-parallel reinforcement integration, application of cover layers and formative and subtractive post-processing of the components, are essential for successful application. In addition, by varying the orientation, characteristics and arrangement of the layers, new shapes and functions can be realised. Examples include angled layer orientation for producing vaulted geometries without support structures, as well as non-planar layer formation for complex component geometries or assembly joints. Moreover, alternative innovative manufacturing processes, such as KnitCrete, Smart Dynamic Casting or Injection 3D Printing, reveal new potential for the application of digital manufacturing technologies in the construction industry. This article aims to demonstrate the possibilities offered by digital fabrication with concrete beyond the stacking of horizontal planar layers, and how these technologies can complement and expand a future digital fabrication strategy in the construction industry.

1. The versatile opportunities of digital fabrication with concrete - a systematic approach

The construction industry recently witnessed a paradigm shift with the emergence of (concrete) 3D printing technology. For the construction sector, 3D printing is an ideal digital fabrication technology as it combines the advantages of automation and customisation. 3D printing promises unprecedented possibilities in the realm of ecological, sustainable, and efficient building practices. It stands out as a transformative technology with the potential to minimise the carbon footprint by optimising material usage [1] while being both fast and productive [2] when precisely depositing strands with robots.

However, most works focus exclusively on printing horizontal planar concrete strands. Alternative innovative 3D printing processes, or possible combinations of conventional 3D printing with other digital manufacturing processes are not given enough attention.

Therefore, this article aims to highlight and integrate various digital processes that extend beyond horizontal planar layers. We focus on holistic approaches that consider the material, the process, and the design in an integrated manner for digital concrete fabrication. Thus, in addition to 3D Concrete Printing techniques, we discuss digitally controlled concrete casting, surface trowelling, and milling technologies. By examining these processes together, we seek to promote more sustainable construction practices through advanced digital methods.

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Fig. 1 shows a systematic overview of the versatile opportunities offered by digital fabrication with concrete. The focus here is on processing fresh and green concrete (partially cured but not fully hardened). The use of digital assembly technologies with hardened precast concrete parts is not included in this discussion. The categorisation of fabrication strategies discussed is based on the process classification by Buswell et al. [3,4], which defines and describes Digital Fabrication with Concrete. According to this framework, there are three primary process classes: additive, formative and subtractive. In Fig. 1, these process classes are detailed as follows: (1) Digital 3D Printing [additive], (2) Digital Casting [formative], (3) Digital Trowelling [formative] and (4) Digital Milling [subtractive].

Digital 3D Printing processes are primarily characterised by the deposition and stacking of material layers. The classification is based on the orientation, characteristics and arrangement of these layers. Additionally, the support for the material layers is a key distinguishing feature. In this context, a basic distinction can be made between four types of 3D printing technologies (I) Printing without support, (II) Printing on (existing) Core Components, which can be fabricated using either conventional or 3D printing technologies, (III) Printing in Carrier

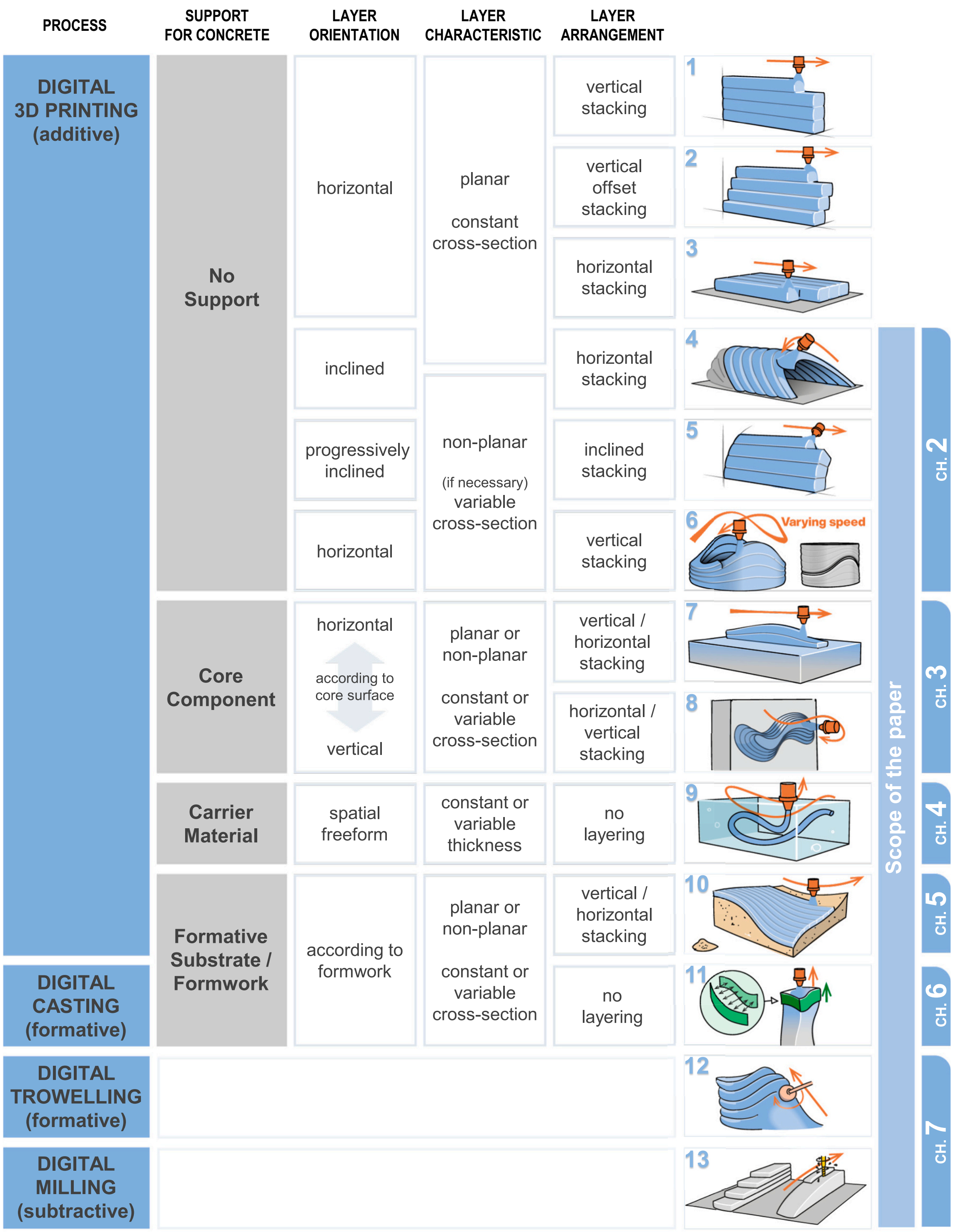

Fig. 1. Digital fabrication strategies with concrete.

Material and (IV) Printing on Formative Substrates, i.e. temporary formwork. The temporary formwork acts as an interface to Digital Casting technologies, which are characterised by the continuous casting of set-on-demand concrete.

Printing with horizontal planar layers without support characterises the most common 3D printing techniques. The layers can be arranged directly on top of each other, with an offset, or next to each other, allowing the production of vertical and inclined components such as walls and columns or horizontal components like ceilings; see Fig. 1 top 3 rows. However, these processes do not fully exploit the potential of digital fabrication technologies in terms of freedom of form. For instance, in extrusion 3D printing, overhangs typically range from 20° to 45°, depending on material properties and layer hardening rate specific to the process [5,6]. This restriction affects the opportunities for structural performance, functional integration, resource efficiency and architectural design. To address these limitations, a variety of digital fabrication technologies beyond horizontal planar layering have been developed and investigated in recent years.

The range of shapes achievable with conventional deposition-based 3D printing techniques expands when the layers are oriented in ways other than horizontally. This includes printing inclined or non-planar layers with varying cross-sections; see Fig. 1, rows 4 to 6. Inclined layers allow highly inclined structures or even arched structures to be realised. Non-planar layers can be used to directly print, e.g. geometric structures for joints; see Section 2.

Using 3D printing on existing core components expands the range of potential applications; see Fig. 1 rows 7 and 8. Here, the concrete is supported by the core component, which determines the initial layer orientation. Despite this, it is possible to produce planar and non-planar layers, layers with constant or variable cross-sections and layers arranged both horizontally and vertically. These techniques enable additional structural elements to be 3D printed onto existing concrete components using hybrid manufacturing processes. They can also be used to create functional surface structures by applying plaster, structurally embed the reinforcement into existing building components by robotically spraying a cover layer, and realise ceiling decorations or overhanging applications on façades; see Section 3.

Injecting into a carrier material is a novel type of additive manufacturing method, where the injected material is supported by the carrier material; see Fig. 1, row 9. With this method, the limits of layer-by-layer 3D printing are overcome, allowing for printing freeform concrete strands into three-dimensional space for high-resolution spatial structures, among other things; see Section 4.

Printing on Formative Substrates methods complete the range of Digital 3D Printing processes. Here, temporary, rigid, adaptive, or flexible formwork is used to support the concrete; see Fig. 1 row 10. These formative substrates enable free-form load-bearing structures to be realised, whereby the formwork determines the initial alignment of the layers; see Section 5.

In addition to additive manufacturing, the formative *Digital Casting* techniques offer various promising processes for digital fabrication with concrete; see Fig. 1, row 11. These techniques involve the use of temporary or permanent formwork to realise free-form components. However, unlike additive manufacturing, concrete is not deposited layer-by-layer. Instead, it is processed in a digitally controlled casting process coupled with set-on-demand admixtures to control the rheology and hydration of the concrete. This allows the use of minimal slip formwork or very thin static formwork such as millimetre paper, and the process allows the integration of standardised reinforcement; see Section 6.

Finally, *Digital Trowelling* and *Digital Milling* processes can be used in hybrid or successive processes to enhance Digital 3D Printing processes; see Fig. 1 rows 12 and 13. This enables overcoming the limitations inherent in additive manufacturing, such as precision and surface finish, and either improving the component properties or supplementing them with additional functions; see Section 7.

In the upcoming sections, we will delve deeper into each technology and discuss its relevance in the realm of digital fabrication with concrete. We will, therefore, describe the processes, provide specific examples, and address the opportunities, challenges, and future developments.

2. Inclined and non-planar layer printing

2.1. Process

3D printing of unsupported overhangs, sloped structures, arches, or structures curved in z-direction by layered deposition 3D printing techniques can be realised by applying the material along print paths that are not horizontal and/or by printing non-planar layers; see Fig. 1, rows 4 to 6. Typically, this process employs a more intricate motion pattern, positioning the printing tool at an angle different from the vertical axis to achieve inclined layers. The inclined layers can vary in cross-section to ensure a consistent slicing strategy. Non-planar layers can be realised by active-z printing [7], involving a simultaneous motion of the print head in the x-, y- and z-axis, or by variable material deposition rates. The first method often requires an existing structure on which the non-planar layer can be printed (see Section 3), while the latter can be realised without additional support. A variable deposition rate of the concrete is typically regulated by adjusting the printing speed at the nozzle, i.e. altering nozzle traverse speed, rather than changing the pump's flow rate [8,9]. The variable deposition rate results in concrete strands with a variable cross-section. This characteristic is particularly relevant to extrusion techniques that produce a formable filament, often referred to in the literature as “free-flow” regime after extrusion [9]. Free-flow deposition relies on material properties that exhibit a rapid stiffening rate of the filament (multi-K 3D printing) rather than a high initial yield stress [10–13].

2.2. Opportunities and current applications

Inclined and non-planar layer printing is predominantly utilised for funicular geometries [14–16], among which the most common in 3D printing is the Nubian vault method [15,17]. In traditional construction, Nubian vaults allow the construction of arched structures with self-supporting discrete brick or stone rows, where the vault is formed by gradually extending these rows until they converge into a curved structure with no formwork. Similar to bricks in Nubian vaults, inclined-arranged concrete strands can be stacked to create stable, unsupported vaults; see Fig. 1, row 4 and Fig. 2. This strategy illustrates an effective use of inclined and non-planar layer printing for structures with a mainly horizontal orientation, such as slabs, showcasing a material-saving application in construction [18,19].

Other examples include Extrusion 3D Printing using the Tangential Continuity Method to generate the printing path [20] and the Gradual Transition Shotcrete 3D Printing technique [13,21,22], in which the inclination of the layers is progressively changed; Fig. 1, row 5. With Shotcrete 3D Printing (SC3DP), the high speed of the concrete application ensures a particularly strong interlayer interlocking in the fresh state [21]. This enables seamless transitions from horizontal to vertical planes, creating new possibilities for geometric designs in 3D concrete printing [22]. Fig. 3 shows a funnel-shaped structure with a height of 1.2 m, a baseplate radius of 40 cm, and a top radius of 1.8 m. Starting with a cylindrical extrusion up to 50 cm, the shape then gradually widens as the projection angle changes by one degree per revolution. The structure reached a height of 1 m in a printing time of just 15 min, with the nozzle positioned at a 60-degree angle from the vertical, resulting in a horizontal overhang of 0.4 m.

Furthermore, the method of inclined stacking of non-planar layers is especially useful for branching columns [24], as it allows the concrete layers to be rotated to align perpendicularly with the primary force flow. This orientation is also beneficial for embedding shear reinforcement between layers [25]. The benefits of non-planar layer deposition

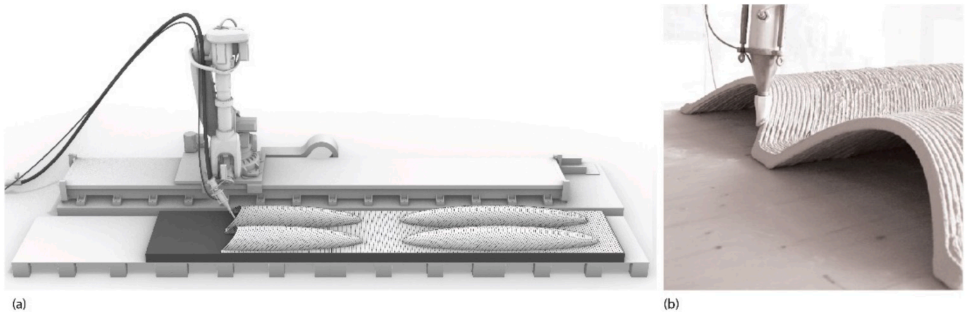

Fig. 2. The Nubian Slab - 3D Concrete Printed stay-in-place formwork for vaulted slabs: (a) upscaling fabrication [18]; (b) material deposition by horizontal stacking (Photo: Andrei Jipa, Digital Building Technologies ETH Zurich).

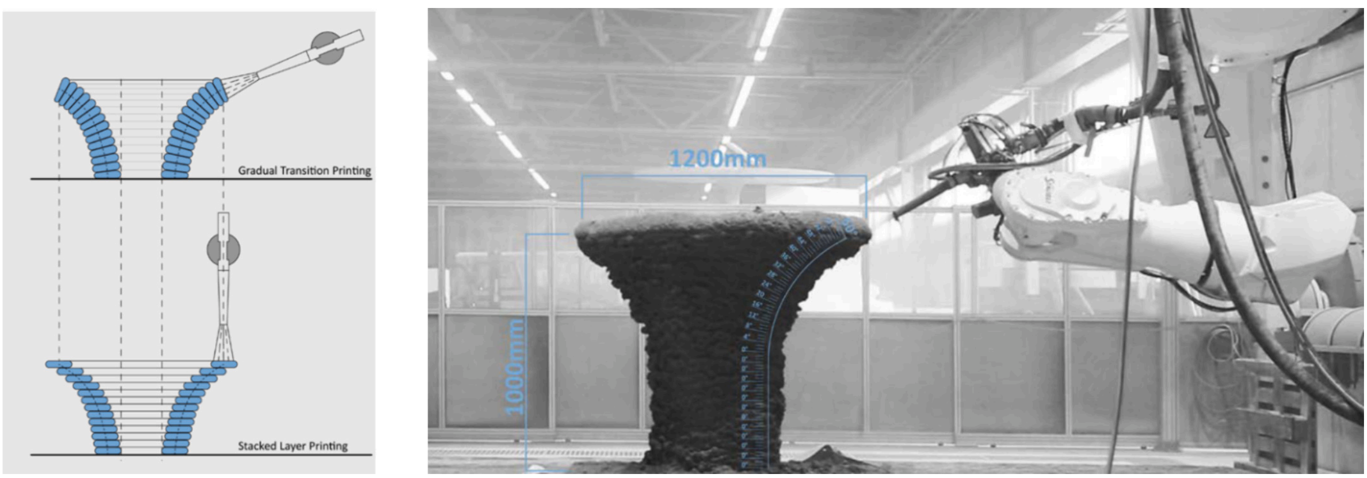

Fig. 3. Gradual transition shotcrete 3D printing [22,23].

significantly improve the constructability of segmented columns and slabs in prefabrication. This technique can inform the alignment of layers with the force flow and create high-precision assembly interfaces, enhancing structural integrity and ease of assembly; see Fig. 4.

Beyond merely shaping the concrete, non-planar layers can also be used to achieve force flow-compliant reinforcement integration. Here, the technique of interlayer reinforcement is used, with the concrete serving as a support for the reinforcement [26–29]. The concrete layers can be formed using non-planar layers that follow the main tensile stress trajectories. This ensures that any flexible or appropriately bent reinforcement placed between the layers is automatically orientated according to the flow of forces [28]; see Fig. 9 and Fig. 10.

2.3. Challenges and future developments

Challenges in non-planar layer deposition stem primarily from the added geometric complexity. This translates to the need for improved material performance during printing, as there is limited tolerance for variability in flow behaviour. Therefore, the specialized 3D printing equipment and necessary additives lead to increased hardware and material costs. Moreover, these methods often demand custom slicing strategies, which require more design time and further elevate costs. Addressing the complexity of assembling freeform 3D printed components and detailing the interfaces between 3D printed and conventional parts also presents significant design challenges. These factors strongly highlight the importance of closing the loop between design and fabrication. Future developments should bridge the gap, ensuring a more integrated and efficient process that links the layer to the overall design strategy.

Fig. 4. Assembly interfaces for segmented columns (Digital Building Technologies ETH Zurich): (a) Vertical stacking of non-planar layers with variable layer height [8]; (b) 3D Printed branching columns: Incremental rotation of layers to align layers to main loads [25]; (c) Tor Alva - match casting for segmental assembly [25].

3. Printing on Core Components

3.1. Process

In this approach, printed layers are applied to an existing core structure; as shown in Fig. 1, rows 7 and 8. The core structures may be an existing building structure or prefabricated elements, conventionally by casting concrete in a formwork or using additive manufacturing techniques. 3D printing is carried out on the core components, either immediately after fabrication of the core, 'fresh-in-fresh', or in the hardened state. When printing on a core component, all the printing techniques described in Section 2 for creating inclined and non-planar layers can be similarly employed. Beyond that, for vertically aligned core components, it is also possible to print vertical layers that can resist gravity; see Fig. 1, row 8.

Printing on Core Components often involves robot-assisted, spray-based additive manufacturing processes. The spraying is executed from an adaptable distance to the surface of the core component, allowing for the deposition of the material in a wide range of surface geometries or patterns, including hard-to-reach areas such as ceilings, corners and edges, where multiple building elements meet. The use cases for Printing on Core Components are diverse. They include:

(1) The addition of structural parts in hybrid manufacturing processes, as with SC3DP Add-On Printing [27,29]; see Fig. 5,
(2) The deposition of plaster to create bespoke or standard functional surfaces on the building structure, as with Robotic Plaster Spraying (RPS) [30]; see Fig. 6
(3) The application of a cover layer for the structural embedding of reinforcement or the realisation of architectural concrete surfaces, as with SC3DP Cover Layer Printing [27]; see Fig. 7.
(4) Functional coatings, overhanging applications on façades and ceiling decorations, as shown by Spray-based 3D concrete printing (S-3DCP) [31,32]; see Fig. 8.

The possibilities and challenges of these printing techniques on core components will be illustrated in the following sections, using the examples of SC3DP Add-On Printing and Robotic Plaster Spraying.

3.2. Addition of structural elements in hybrid manufacturing

Most current 3D concrete printing applications consist of monolithic

Fig. 5. Add-on Printing of force-flow-optimised concrete ribs of a point-supported slab [27,29]. The concrete rips have varying cross-section heights according to the course of the bending moment (Technical University of Braunschweig, 2019).

Fig. 6. Robotic Plaster Spraying (RPS) introduces a gravity-resisting, vertical thin-layer spray-based printing technique (ETH Zurich, 2021) [30].

Fig. 7. Cover Layer Printing using Shotcrete 3D Printing (SC3DP, Technical University of Braunschweig, 2020) [27].

manufacturing processes: Either entire buildings are printed in one piece and from one material or buildings are assembled from individual parts that are produced using the same printing process and the same materiality. Add-On Printing is a hybrid manufacturing method that combines different manufacturing processes and materials and is particularly interesting for enhancing flat components such as walls and slabs with 3D-printed layers. Here, concrete layers are printed selectively on the core component in order to complete or strengthen it; see Fig. 1, row 7. For load-bearing components, these structural add-ons create new possibilities for material-efficient structures with a force-flow-optimised shaping.

Kloft et al. [27,29] first introduced the Add-On Printing technique for the production of reinforced concrete ribbed slabs using Shotcrete 3D Printing; see Fig. 5 and Fig. 9. The flat concrete slabs were conventionally cast as thin as possible and then printed ribs were added "fresh-in-fresh" in accordance with the structural requirements. The printed ribs were fabricated with varying cross-sectional heights according to the course of the bending moments in the case of uniaxially tensioned ceilings; see Fig. 9; or with ribs shaped according to the force flow in the case of the 16 m^2 segment of a point-supported slab; see Fig. 5. With the latter, the thickness of the cast concrete slab part is only 8 cm, which

Fig. 8. Spray-based 3D Concrete Printing (S-3DCP, NTU Singapore, 2024) [31,32].

Fig. 9. Add-on Printing of (a) concrete rips with varying cross-section height according to the course of the bending moment [29].

means a material saving of approx. 60 % compared to a 25 cm thick conventional flat ceiling.

Fig. 10 shows the process steps for an uniaxially tensioned slab segment with three printed, parallel ribs. In addition to the variable cross-section height of the ribs to create a shape affine to the moment line, the required longitudinal reinforcement can be installed without additional structural auxiliary reinforcement; see Fig. 10a. The robotic printing process is stopped when the reinforcement position is reached, and the longitudinal reinforcement is placed on the freshly printed concrete layer; see Fig. 10b. The shear reinforcement inserted in advance when concreting the floor slab is used to position and secure the position. Once the longitudinal reinforcement has been applied, the printing process continues, and the reinforcement is covered with concrete; see Fig. 10c. The bond between the slab and the 3D printed ribs can be ensured by carrying out the Add-On Printing process directly on the freshly concreted core element. This enables chemical bonding, but also good mechanical interlocking, as the high kinetic energy when spraying the concrete results in a rough interlayer zone. If the core elements themselves are also 3D printed, good mechanical interlocking also results from the layered surface structure of the core components; see Fig. 11.

The hybrid manufacturing of individualised ribbed ceilings by locally printing concrete layers onto the freshly concreted ceilings in a continuous automation process is an ideal application scenario. As concrete ceilings in building construction are flat 2D surface components, the formwork and concreting of reinforced concrete ceilings will continue to be an economical solution in the future. However, in recent decades, the trend in long-span reinforced concrete slabs has been away from the originally material-efficient ribbed and beamed slabs towards the mass-intensive point-supported flat slabs. The reason for this development is the low formwork costs of flat slabs compared to ribbed and beamed slabs, which clearly outweigh the additional costs on the material side. With the focus on material-saving and low-CO_2 construction approaches, material-saving ribbed and beamed ceilings are once again gaining in importance. By combining traditional concrete casting with innovative 3D printing technologies, one can produce high-performance, material-efficient slab components and make the manufacturing process extremely economical by eliminating the need for complex formwork. In addition, the change in manufacturing technology also offers the possibility of changing materials and, thus, a further optimization option. In terms of design, sophisticated slab undersides can be created that make the flow of forces recognizable.

Beyond that, add-ons also create completely new possibilities for material- and production-efficient applications. Fig. 11 shows the subsequent Add-On Printing of a bracket on a previously printed wall component. Here, the inserted short rebars provide a sufficient shear connection between the printed wall component and the add-on printed bracket [33].

Fig. 10. (a) Add-on Printing of concrete rips with varying cross-section heights (b) Application of the longitudinal reinforcement bars (c) Application of the concrete cover onto the reinforcement [29].

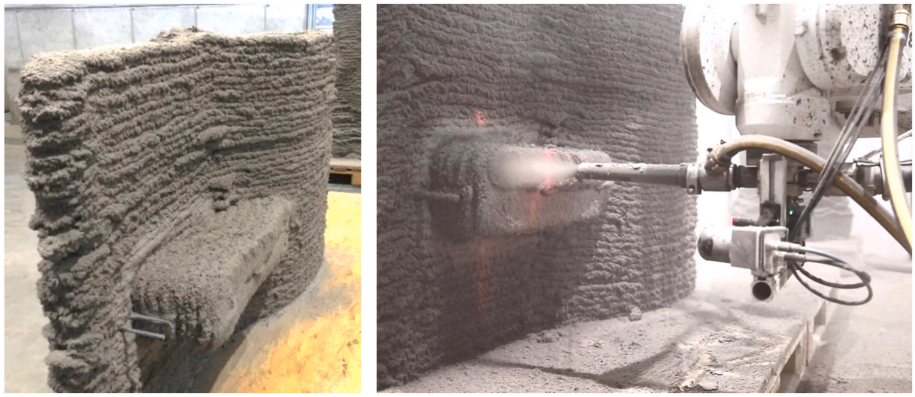

Fig. 11. Subsequently, additively manufactured concrete bracket on a wall using SC3DP Add-On Printing (TU Braunschweig).

3.3. Addition of plaster layers

Robotic Plaster Spraying (RPS) [30] involves the spraying of multiple, millimetre-thin, and vertical layers of plaster to building elements, which is then repeated to build-up 3D-formations in an additive-only fabrication process, producing minimal waste. It offers shaping free-form, bespoke designs, directly on the building structure; see Fig. 12. The material deposition is facilitated through a pneumatic spray gun, which is equipped with a nozzle at the tip. The material volume flow is kept constant, while the velocity of the robotic arm, the spraying distance from the target substrate surface, and the nozzle diameter of the plastering spray gun control the feed rate, thus determining the amount of material sprayed onto the target surface in each layer. By optimising process parameters, such as the distance, angle, and speed of the robotic arm, the material formation can be accurately controlled, and the intended surface geometry or pattern can be created. Therefore, the "tool" in the proposed technique is the digital control of the spraying that is activated by air pressure and that allows for forming the material directly on the building structure. In this way, the malleability of the material combined with the digitally controlled, pneumatic spraying method acts as a kind of "dynamic formwork" for the resulting surface geometry; see Fig. 12.

It is worth noting, that the setup for the Robotic Plaster Spraying comprises a mobile platform on which the robotic arm is mounted. The uninterrupted motion of the robotic platform enables *printing-in-motion* [34,35]. In initial investigations on the printed geometry accuracy, the deviations did not exceed ±2 cm. However, further testing will be necessary to assess the implications of the mobile robotic system and continuous spray-based printing-in-motion on how the error manifests throughout the whole printed geometry.

3.4. Opportunities, challenges and future developments

Printing on Core Components introduces new degrees of design freedom for structural efficiency, functional integration as well as aesthetic articulation. By spraying multiple layers of concrete or plaster onto a building structure, the incremental build-up of 3D formations is enabled without the use of additional smoothing or profiling tools, formwork, or support structures. The robotic process can be extended to explore different roles of the concrete cover layer or plaster, i.e. durability, insulation and weather protection to the building structure. At the same time, additional functions can be integrated, for example, to provide visual, acoustic, or light-diffusing effects through geometric complexity. Furthermore, in addition to new constructions, repair and strengthening of existing building structures constitute a particularly interesting potential with printing on core component techniques, [36].

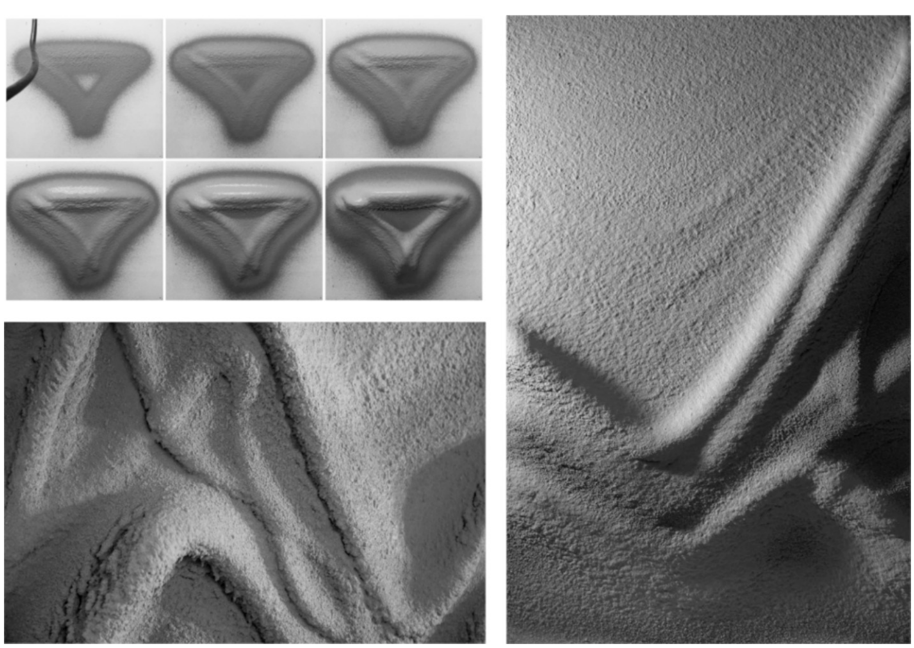

Fig. 12. Prototypes produced with RPS - spraying of multiple, millimetre-thin, vertical layers of cementitious plaster to building elements [30].

The research into printing on core component techniques is in its early stages, seeking to understand how the material and its geometric complexity can correlate to performative qualities. When scaling up, further knowledge regarding the material properties, such as the pull-off strength of the applied layers, is essential. Moreover, it is decisive to consider the compatibility of the materials used for the core component and the printed layers in terms of strength, deformability, shrinkage, and creep to ensure the performance of the combined load-bearing structure. Furthermore, considering the existing building structure and the as-built state of the printed layers will be crucial for making the necessary adaptations, corrections, etc., interactively and on the fly.

4. Injection in Carrier Material

4.1. Process

The basic principle of this technique is that a material (A) is robotically injected into a carrier material (B). The carrier material (B) can either be a non-Newtonian fluid with specific rheological properties or a granular material. When mastering the process properly, material (A) remains in a stable position within the material (B) [37,38]; see Fig. 1, row 9.

Examples of Injection in Carrier Material techniques are Injection 3D Concrete Printing (I3DCP) [39,40]; see Fig. 13a-c; or Non-Planar Granular Printing (NGP) [40]; see Fig. 13d. Non-Planar Granular Printing was conceptually explored by injecting a resin into a box filled with sand [40]. Although it is technically not yet concrete, the injection of cement paste is conceivable in principle with this method. The basic principle of Injection 3D Concrete Printing is shown in Fig. 13a-c. It has been applied in three variants: (1) Injection of a fine-grained concrete into suspension (CiS), i.e. into a non-hardening, non-Newtonian carrier liquid; see Fig. 13a; (2) Injection of a non-hardening suspension in concrete (SiC); see Fig. 13b; and (3) Injection of Concrete in Concrete (CiC), typically with different properties of the two concretes, e.g. a high-strength concrete into a low-strength concrete; see Fig. 13c.

4.2. Opportunities and current applications

Injection in Carrier Material introduces entirely new formal and tectonic possibilities: It enables 3D printing in limitless spatial trajectories. Furthermore, these techniques eliminate the need for layering materials strands when creating large components [39,40].

Small-scale experiments have been conducted for Non-Planar Granular Printing [40]. The initial objects include the exploration of various granular materials; as shown in Fig. 14. In a similar way, complex truss structures and filigree concrete space frames can be created with the Injection 3D Concrete Printing variant Concrete in Suspension [37,39,41,42]; see Fig. 14c and Fig. 16. These structures are otherwise challenging or impossible to construct. Up to now, ultrasound-gel and limestone suspensions with varying particle sizes and additives have been reported as carrier suspensions [37,38,43,44].

In the I3DCP technique Suspension in Concrete, where a non-hardening material is injected into the fresh concrete and removed when the concrete is hardened, channels or cavities can be deliberately generated. This can be used, for example, to locally grade the concrete density. In addition, it is possible to create openings that can be used as a design element, e.g. look-through façades, or functionally, e.g. for greening the wall; see Fig. 15a.

The I3DCP technique, Concrete in Concrete, uses concrete as injected material but also as carrier liquid. With this approach, it is possible to modify the local material properties according to structural requirements. This allows for the local incorporation of strengthening structures in beams, slabs, walls, or columns, providing a potent method to improve overall performance while reducing the environmental impact; see Fig. 15b.

Beyond these small examples, there are two large-scale pilot structures, demonstrating the potential of Injection 3D Concrete Printing in transforming concrete into lightweight space-frame structures. These have been performed using the Concrete in Suspension technique. The first application was presented by the company Soliquid [42] who fabricated an artificial concrete reef named Bathy Reef. This complex, bio-inspired structure has a large surface area and was constructed to investigate the colonization of the artificial reef. At the Technical University of Braunschweig, an unreinforced arch bridge was fabricated [39]. The structural design method for the bridge relied on 3D graphic statics [45] to create a compression-only structure. The bridge is designed at a 1:5 scale, comprises five components and reveals a total length of 3 m; see Fig. 16.

4.3. Challenges and future developments

The first applications have shown that Injection 3D Concrete Printing allows for the fabrication of large-scale components that are either lightweight and geometrically complex or serve an inner structure with variation of local properties while enabling structural integrity. However, in the future, there are remaining challenges that need to be addressed in further research. The most important aspects comprise the prediction of a successful print based on material properties and the boundary conditions of the process as well as a successful reinforcement integration.

For a successful print, i.e. the stability of the injected material at its designated location with its designated geometry, the material and process parameters need to be chosen properly [38]. However, the relationship between process parameters, material parameters, and positional stability is not fully understood yet and will require further research. Furthermore, 3D printing has only the potential to become a key technology for the digitalisation and automation of the construction industry if the reinforcement integration is technically solved. However, not all concepts for reinforcement integration in additive manufacturing, compare [46], are applicable to Injection 3D Concrete Printing. Initial concepts such as the extruded fibre-reinforced cement paste by Adams et al. [47] or printing around reinforcement preinstalled

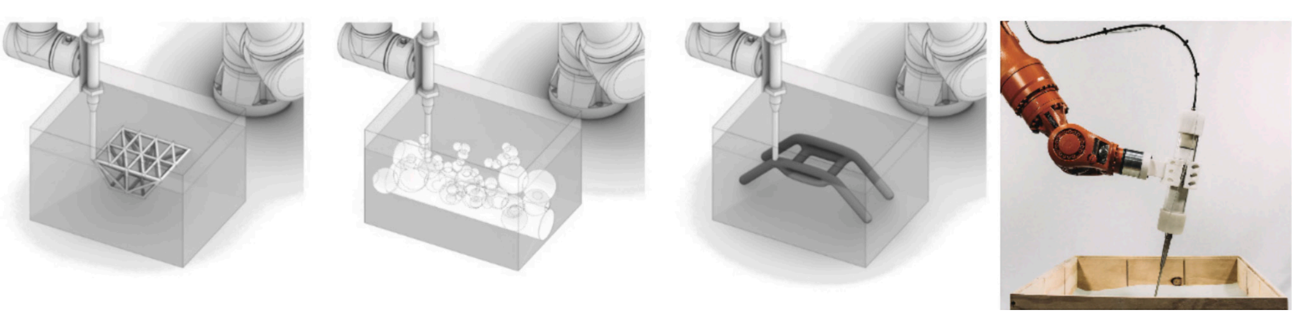

Fig. 13. (a) – (c) Injection 3D Concrete printing (I3DCP) variants (Visualization: Sakiko Noda): (a) Concrete in Suspension (CiS); (b) Suspension in Concrete (SiC); (c) and Concrete in Concrete (CiC) as well as (d) Non-Planar Granular Printing (NGP) [40].

Fig. 14. Non-Planar Granular Printing with different materials: a) glass beads, b) walnut chips [40] as well as c) Injection 3D Concrete Printing using the Concrete in Suspension technique (Technical University of Braunschweig).

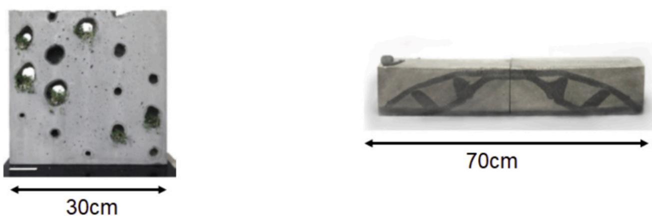

Fig. 15. Injection 3D Concrete Printing variants: (a) Wall segment manufactured using the Suspension in Concrete technique; (b) Cross-section of an internally strengthened beam manufactured using the Concrete in Concrete technique with two different concrete types [30].

in the carrier liquid by Lowke et al. [38] are promising but require further research.

5. Printing on Formative Substrates

5.1. Process

Digital 3D Printing processes can be applied to the construction of concrete structures in two primary ways: the manufacturing of concrete formwork along with a semi-traditional casting process, and the direct manufacturing of the concrete structure or component as described in the previous sections of this paper. This section presents the possibilities of combining these two approaches. In this type of process, a formative substrate, such as temporary formwork, serves as a non-planar guide for applying concrete; see Fig. 1, row10. This can be achieved through 3D printing methods like material extrusion or material jetting, or another digitally controlled process. Research in this field has led to several methods for creating concrete structures using a formative substrate for support. These methods can be broadly classified into three categories of substructures:

(1) Rigid substructures using 3D printed, milled or formed materials: Digitally fabricated formworks made from rigid materials such as timber, foam, and Particle-bed 3D Printing are being increasingly investigated to streamline and decarbonize the construction phase of concrete structures [48]. Any of these formworks could also serve as formative substrates for 3D printing of concrete. Examples where such formworks are used in non-planar 3D printing include the Automated Robotic Concrete Spraying (ARCS) shell developed at the University of Cambridge [49], where several components of a vaulted ribbed floor were manufactured using a robotic shotcreting process onto a rigid curved substructure, and the Fast Complexity project [50], described in Section 5.2. In other examples, the malleability of sand is used to create temporary formworks for conformal 3D printing [4,51–53].
(2) Adaptive formworks: Adaptive moulds, made up of grids of linear actuators, have been widely used for moulding doubly curved composite materials and concrete structures [54]. In concrete applications, they are typically used for direct casting of thin, doubly curved elements [55] like façade panels. More recently, these pin moulds have also been used as substrates for extrusion 3D concrete printing or shotcreting [56].
(3) Flexible formworks using textiles and meshes: Another category of formworks for concrete structures includes flexible fabric formworks, which have been investigated throughout the 20th century as a lightweight alternative to traditional formworks. These formworks have proven useful for a variety of architectural and structural elements, including linear elements (e.g. beams, columns), surface elements (e.g. shells), and intricate branching combinations [57–59]. A recent development in these fabric formworks is the use of 3D knitted textiles, named KnitCrete,

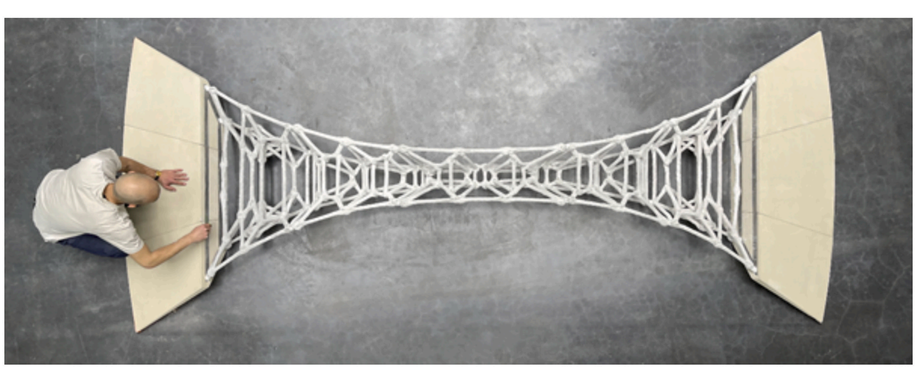

Fig. 16. Assembled 3 m-compression-only-bridge consisting of five individual components [39].

where the tensioned textile is stiffened with a thin cement paste coating before casting concrete [60]. Such a flexible substrate has also been used in conjunction with robotic Shotcrete 3D Printing in a bridge demonstrator collaboratively developed by the Technical Universities of Munich, Delft and Braunschweig [61], described in Section 5.2. Other examples of flexible substrates include meshes and rebars. In these cases, rebar meshes are formed into the desired geometry, and concrete is printed or sprayed onto them. Examples include Meshworks (SCRIM) developed at CITA [62] and Robotic Aerocrete at ETH Zurich [63].

5.2. Current applications with rigid and flexible substrates

The Fast Complexity project showcases a prefabrication method that leverages precise 3D Printing, such as Particle-bed 3D Printing, and layered extrusion techniques to produce custom concrete elements quickly and precisely [50]. Therefore, in the first step, high-resolution printing is used to manufacture a rigid and reusable substrate, which is the underside form of a slab soffit. A thin layer of concrete is then added onto the formative substrate and reinforced with a non-corrosive mat. Subsequently, the reinforcement is embedded again by extrusion 3D printing and finally, the layout of 3D-printed formwork for structural ribs is added on top; see Fig. 17a. These modular, prefabricated elements are then transported to the construction site, where the main ribs receive the steel reinforcement and are cast with conventional concrete on-site to produce a monolithic ribbed slab. Initially focused on slab elements, the methodology is, however, adaptable to various building components as required.

Another representative example is the Knitcrete bridge by Rennen et al. [61]. As a case study combining a 3D knitted textile formwork with Shotcrete 3D Printing, a small pedestrian bridge was computationally designed and robotically concreted in a cross-university effort between the Technical Universities of Munich, Delft, and Braunschweig.

In a digital form-finding process, a shell structure was developed that is tensioned on bending-active boundary elements made of reinforcement steel. This geometry was then manufactured in two symmetrical halves on a CNC knitting machine. The bending-active steel parts were braced between two concrete foundations, and the textile was pulled onto them using the integrated loops. Under tension, the textile thus formed a double-curved membrane. This membrane was then sprayed with a 2 mm thin layer of a cement slurry to “freeze” the shape; as shown in Fig. 18. After the geometry's initial “freezing”, glass fibre reinforcement was applied in a robotic fibre winding process. This was followed by applying layers of concrete up to a thickness of 7 cm using the SC3DP process. Afterwards, a spherical smoothing tool was used for surface structuring, which produced a groove structure that followed the longitudinal direction; see Fig. 19. Finally, the edges of the bridge were finished with a milling tool.

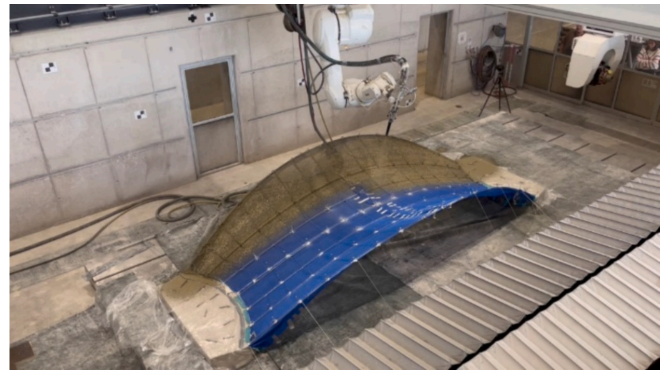

Fig. 18. Robotic spraying of the initial “freezing” layer onto the knitted formwork.

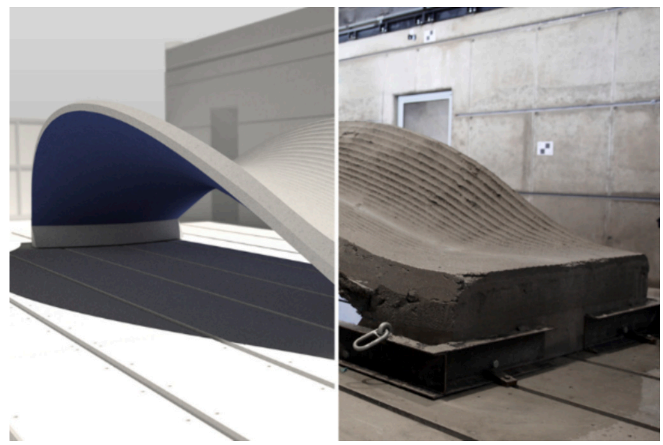

Fig. 19. Overlay of the 3D model and the final bridge structure.

5.3. Challenges and future developments

Concrete structures shaped using formative substrates entail several distinct fabrication steps, each adding to the overall complexity of the process. One of the most challenging of these steps is concreting, which requires non-planar trajectories to avoid collisions with the existing substrate. Additionally, the concrete must adhere properly to the substrate without causing deformations.

Another challenge is the precise positioning of the reinforcement to ensure proper coverage within the component and, thus, providing sufficient bond and corrosion protection. For steel reinforcement, it is essential that the material is precisely pre-bent and placed on the substrate with the correct spacing. In the case of textile reinforcement,

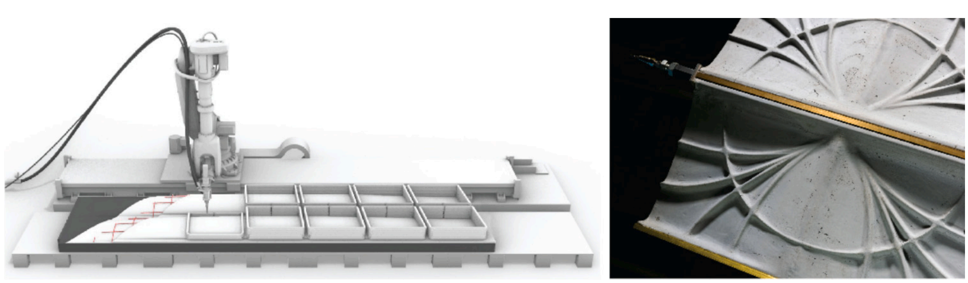

Fig. 17. Fast Complexity - concrete extrusion on a temporary formwork: (a) Procedural concept involving 1. Manufacturing the formative substrate using high-resolution printing, 2. Adding a thin concrete layer by extrusion 3D printing, 3. Adding reinforcement, 4. Embedding the reinforcement and 5. Adding the layout of the formwork for structural ribs on top by extrusion 3D printing; (b) View of the high-resolution soffit (Photo: Axel Crettenand, Digital Building Technologies ETH Zurich).

integrated pins within the formwork enable the reinforcement to be wound around them. A significant advantage of this method is that the pins can be accurately positioned relative to the substrate, such as by integrating them into the rigid 3D printed formwork. Additionally, textile reinforcement is less prone to corrosion and can tolerate minor positional deviations and minimal coverage within the component.

When using flexible formworks, keeping the shape accuracy is an important factor that affects the structural performance of the concrete structure. The main challenge is the inherent flexibility of the material, which requires careful consideration of the fabrication sequencing. For example, accurately determining the quantity and precise location for material placement at specific times is crucial. In the case of KnitCrete, this shape control problem is avoided by building strength in layers by employing first a lightweight coating layer that does not deform the flexible textile formwork and can carry the load of subsequent concrete casting. The scalability of these types of systems also plays a role in future applications. Currently, flexible formworks have been employed at an architectural scale and span considerable areas [59].

These complexities highlight the need for further research in the design-to-fabrication process, particularly by integrating adaptive feedback to align the concreting process with the final target shape. Moreover, further research should explore embedding functionality into the substrate to serve as reinforcement or develop reusable and reconfigurable formwork.

6. Digital Casting

6.1. Process and material control

In parallel to additive manufacturing processes, formative manufacturing processes, i.e. “Digital Casting Systems” (DCS), represent a promising approach for digital concrete. DCS employs a digitally controlled casting process coupled with set-on-demand admixtures to control the concrete's rheological properties and hydration rate during fabrication [64–66]; see Fig. 1, row 11. DCS allows real-time control of self-compacting concrete hydration, reducing the need for heavy formwork and enabling the pre-placement of standard reinforcements that comply with norms. Over the last decade, a number of different processes, covering various formworks, have been developed, including Smart Dynamic Casting (SDC) [67], a dynamic slipforming process, Eggshell [68], using ultra-thin fused deposition modelling formworks, and Admixture Controlled Digital Casting (ACDC) [69] with lightweight formworks made from foil, textile or even millimetre-thin paper formworks [70].

To ensure controlled hydration and homogeneity of the mix during casting, DCS rely on three distinct process steps depicted in Fig. 20. Firstly, the concrete must undergo processing to the point of acceleration, typically achieved by pumping, a concept referred to as “pumpability” in the literature [12]. Secondly, the concrete must be well intermixed with accelerating admixtures in an Inline Mixer and effectively placed in DCS, indicating that it should self-consolidate in a formwork with minimal or no vibration - a crucial step termed “castability.” The third step is referred to as buildability. For slipforming in Smart Dynamic Casting this is particularly delicate, since the concrete needs enough strength to support the weight of subsequent layers without collapsing or undergoing significant deformation at the formwork exit during the slipping. For thin formworks (ThinForm), the process is less delicate in terms of collapses; however, it does require a fast strength build-up to prevent the formwork from bursting. These processing steps come with inherent limitations and boundaries, primarily influenced by material characteristics and processing considerations. To ensure homogeneity, a specific mix design is tailored to the project's requirements, with real-time adjustments of the concrete's hydration rate and viscosity. Daily modifications may be necessary to respond to temperature fluctuations, ensuring consistent flow, compaction and, ultimately, void-free structures.

In comparison, for 3D Concrete Printing (3DCP), buildability requires a yield stress high enough to prevent the layers from collapsing, while simultaneously not hardening too fast to avoid cold joints. A key distinction between the DCS and 3DCP lies predominantly in the casting/deposition step, where DCS demands a lower yield stress compared to 3DCP [71–73]. Due to this lower yield stress, DCS relies on support through the slipform or thin formwork systems, which come with some geometrical constraints and advantages regarding surface quality and the ease of including standard reinforcement. This approach also promises viable methods to cast material-optimised structures. In what follows, we present projects that showcase how rethinking formwork with Digital Casting Systems can open new ways to realise steel-

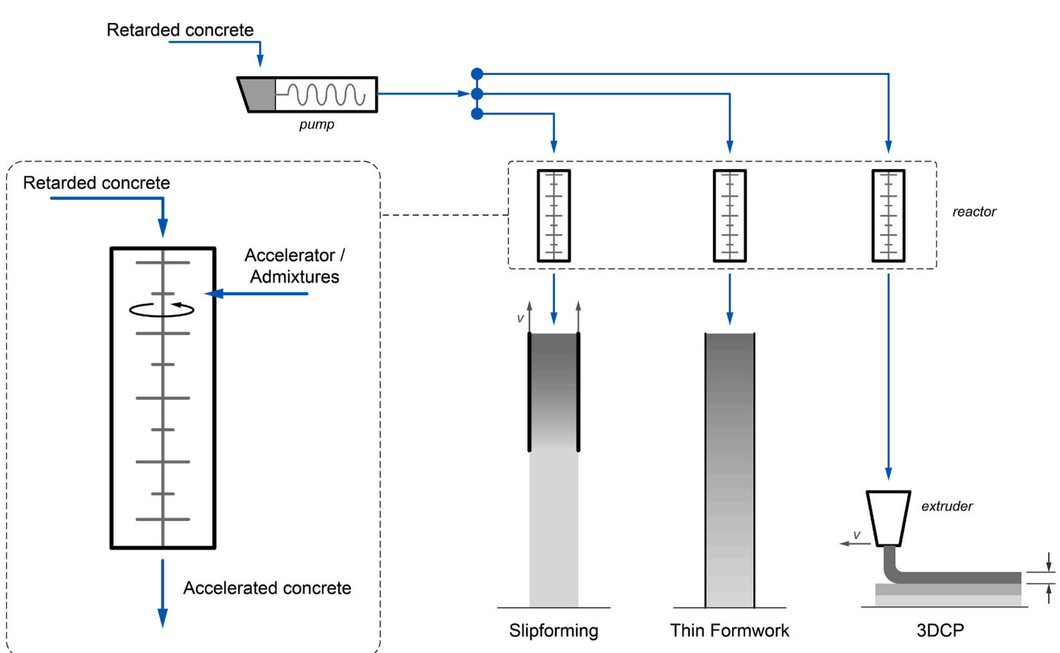

Fig. 20. Schematic overview of the Digital Casting process: Left: pumping retarded concrete into the inline mixer. By adjusting the rheological properties during the casting, the same system can be used for Smart Dynamic Casting (SDC), ThinForm and even for Extrusion 3DCP [11].

reinforced material-lean structural concrete elements.

6.2. Robotic slipforming

Digital Casting Systems was pioneered in 2012 with Smart Dynamic Casting, a robotic slip-forming process [65,74,75] used to produce reinforced standard and non-standard columns up to a height of 1.9 m; see Fig. 21a, [67]. Since then, SDC has evolved into a system that enables the production of structurally optimised and easily reinforced shapes, with excellent surface quality while also including conventional reinforcement, in accordance with existing norms [76]. The key technology behind SDC is the set-on-demand process controlled through a Digital Casting System, where a stream of retarded concrete is accelerated and cast into a moving formwork significantly smaller than the structures produced. The formwork moves at a speed synchronised to the hydration rate of the concrete, assuring that the material is buildable at the formwork exit, or in other words, that it can sustain its own weight and the weight of the material inside the form.

SDC was successfully implemented in the architectural project DFAB HOUSE [77], where 15 mullions were individually fabricated for the façade's load conditions using a single formwork; see Fig. 21b. In contrast to standard construction, which necessitates 15 individual formworks for minor load variations, SDC enabled the production of 15 bespoke mullions. This innovation resulted in a 30 % reduction in materials compared to placing 15 standard mullions with the same dimensions, showcasing the practicality of material-economic production. The mullions serve as a tangible demonstration of efficient production and represent the lower limit of achievable dimensions within this system. It is also noteworthy that friction increases with a decrease in cross-sectional area, as discussed in the studies of Szabo [78] and Schultheiss [79]. Thus, expanding the geometric complexity to handle highly intricate structures would necessitate additional research, particularly in relation to formwork and processing.

6.3. Thin formworks

The limitations and geometrical constraints of SDC led to the development of systems known as Eggshell utilising an ultra-thin formwork fabricated through Fused Deposition Modelling (FDM); see Fig. 22. These formworks are subsequently filled using a Digital Casting System, which, thanks to setting-on-demand and digitally controlled processing, exerts minimal pressure on the formwork.

Two applications of Eggshell were demonstrated in construction scenarios. Firstly, in the Future Tree project [68], a reinforced concrete column that serves as a support for a reciprocal wood structure [81]; see Fig. 22a and b. Secondly, in the Vitra Pavilion [82]; see Fig. 22d. Here it is noteworthy that the formwork was recycled from the Future Tree, demonstrating the recyclability of the formwork [83]. Eggshell technology was utilised for producing columns with DCS. Simultaneously, the slabs were formed using eggshell formwork but cast with conventional Self-Compacting Concrete (SCC). This decision is rooted in the observation that formwork pressure becomes non-critical for formwork heights below 40 cm. The advantage of using eggshell with standard SCC is that we could reduce materials by 40 % compared to a standard slab, thanks to the optimised geometry achievable with the recyclable Eggshell formwork [84].

Additional exploration into the use of thin formworks was conducted by Szabo [85]. She examined the utilisation of weakly supported formworks constructed from suspended foil, textiles, rammed boards, and even paper supported by a weak wooden frame; see Fig. 21c. These formworks were filled using a Digital Casting process called ACDC (Admixture Controlled Digital Casting) to manufacture post-tensioned thin-folded members [69,86]. The outcomes illustrate an economically viable method for producing formwork tailored for non-standard

Fig. 21. a) Smart Dynamic Casting: Robotic Slipforming with flexible formwork [78], b) DFAB House, image Gramazio Kohler Research [80], c) ACDC Supported Thin Formwork [69].

Fig. 22. a) Future Tree, Esslingen, Switzerland [81], b) Formwork for Future Tree [68], c) Post-tensioned columns with Eggshell [68], d) Vitra Pavillion [82].

shapes, specifically for thin-folded and reinforced plate structures.

6.4. Paper formworks

A more recent study referred to as "Increase", highlights the potential of using millimetre-thick paper as a formwork with DCS [70]. This work first tested the feasibility of folded elements and then of columned sections up to a height of 2.5 m; see Fig. 23. As such, it merges two seemingly paradoxical materials, namely heavy concrete, and lightweight paper, something made possible thanks to the set-on-demand DCS. The utilisation of paper is facilitated by stiffening it through the principles of folding. This is promising and offers a wide array of possibilities [86,87]. To produce the column, a rebar cage was placed into the formwork prior to casting, like the eggshell column. The material processing was successfully carried out with DCS, where an automatically adjusted flow rate between 1.5 and 3.0 l/min compensated for the changing cross-section. The total casting time was approximately 100 min, although this may vary ±20 min depending on the behaviour of concrete hydration.

6.5. Opportunities, challenges and future developments

As highlighted DCS offers additional possibilities for producing structurally informed elements with non-standard shapes. In contrast to Digital 3D Concrete Printing techniques, it still relies on separately produced formworks but avoids various shortcomings of 3DCP. It facilitates the incorporation of standard reinforcement systems, making it less cumbersome to certify load-bearing structures. It also eliminates

Fig. 23. a,b) Thin Folded elements [85], c) demoulding of first column, d) formwork for column, e) demoulded column produced with DCS [87].

cold joints, reducing durability concerns and, when paper is used, provides an excellent surface finish. For these reasons, DCS is also being implemented as part of an R&D study within a prefabrication plant [88], aimed at developing a robust system for casting non-standard structures using ultra-thin formwork. This approach aligns with sustainability goals by minimising material waste, reducing energy consumption during construction, and enhancing the longevity of structures through improved durability and structural integrity.

The core of the DCS is the set-on-demand system and the corresponding control of the structural build-up of the concrete and the casting speed for the different DCS techniques. In this context, additional research is required to establish the limits of casting speed and hydrostatic pressure, in particular for folded paper formwork. It is essential to investigate how certain folds in the formworks are affected by pressure to determine the upper and lower bounds of those parameters. Ongoing research, not covered in this paper, is actively exploring ways to genuinely achieve this.

7. Digital Trowelling and Milling

7.1. Process

The previous chapters have shown a range of Digital 3D Concrete Printing and Digital Casting methods. A challenge for 3DCP and mouldless material deposition processes, in general, is the visibility of the layers, which are dictated by the dimensions of the material deposition process, i.e. extrusion or spraying. The deposition process heavily influences the surface quality, shape, accuracy and precision as well as the limits of reproduction (resolution) of features, regardless of the orientation of the deposition process [89,90]. There are two principal issues: (1) the layering or deposition effects are not always desirable; a smoother surface is desired, for example; and (2) the resolution of the designed features is higher than what can be produced with deposition alone. Digital Trowelling and Digital Milling technologies enable the processing of components and their surfaces to address these issues; see Fig. 1, rows 12 and 13.

Trowelling. Digital Trowelling can be used when the material is in the plastic state (a) for surface finishing to achieve smooth surfaces up to architectural concrete quality [17,33,91] or (b) to create specific surface textures [61,92]. When applied in combination with 3DCP, typically the bulk volume of the component is printed undersize, allowing for additional material to be deposited and trowelled to the correct surface geometry [93,94].

Milling. By introducing subtractive manufacturing as an additional step in manufacturing, the printed material can be trimmed with far greater precision, [89,90]. In this approach, the printed material is printed slightly larger than needed, allowing the milling to cut back the material to form the final geometry. It can be carried out in the fully hardened state [95–97], but will typically require heavy machine tools and wet cutting to help control the heat generated, and hence the degradation in cutting tools [91]. If implemented when the material is in the post-plastic, i.e. 'green' state, use of the lighter robotic arms, typically deployed for 3DCP, can be utilised while also reducing the energy required and heat, prolonging tool life [98].

Automation. Combining processes in this way have been called hybrid processes [3] and would be controlled digitally based on a CAD model of the desired geometry, termed the 'net shape'. This needs to be 'inflated' (made bigger for milling), or 'deflated' (reduced for deposition and trowelling) so that once the printed component is complete, the overall volume can accommodate the next process, what is called the 'near-net-shape'. Integrating trowelling or milling tools with printing tools onto the same robotic arm via a tool changing system enables automation between manufacturing steps, removing the need for manual operations during the production of a component. For example, in the hybrid printing and milling process, the object would be additively manufactured in the production cell, and once complete, production pauses while the material hardens to the ideal state for milling [92]. The tools would be swapped to enable the milling to be accomplished in the 'milling window' before the material becomes fully hardened. Combining two production steps within the same manufacturing cell under digital control is a step towards better control and more systematic operations, reducing the need for manual intervention, which will (hopefully) lead to increased quality and productivity.

7.2. Opportunities, challenges and current applications

Formative trowelling processes have been applied to a material in a plastic state to improve the surface finish, which could be smooth or textured. Researchers at Carnegie Mellon University undertook investigations to robotically apply plaster to wall segments and mould them using various mechanical tools. The geometric shapes created in the process fulfil both aesthetic and thermo-acoustic functions [92]. One challenge in this process is to produce 'flawless' surfaces, which the researchers are addressing using machine learning for error detection and correction [99].

In the context of Cover Layer Printing for structurally embedding various reinforcement types, such as pre-bent steel or robotically applied glass fibre, on a 3D printed concrete wall, the surface of the cover layer was subjected to a subsequent surface finishing process [94,100]. To produce a high surface quality, the cover layer of shotcrete was smoothed with various rotating trowels and smoothing discs; see Fig. 24. The same strategy was also used for the Knitcrete bridge described in Section 5.2, except that instead of creating a smooth surface, here a pronounced surface structure was deliberately left visible [61]; see Fig. 19.

Subtractive milling to create surfaces and details can be carried out in the green or the hardened state of cement-based mortars or concretes [95–97]. Digitally controlled treatments in both states are in their infancy, and there are relatively few articles that demonstrate the process. To the best of the author's knowledge, academic articles referring to the milling of green cement-based materials are presented in Table 1 focused on surface finishing and feature generation. Milling in the hardened state and been demonstrated to produce smooth edges on a part that has been manufactured using a Particle-bed Binding approach [96], and in forming joints [97].

Fig. 25 depicts a panel component manufactured at Loughborough University demonstrating the milling during the green state. Next to this is a comparison of the printed and milled finishes in the hardened state and demonstrates the increase in surface and feature detail that is possible [97].

There are significant benefits to combining towelling and milling with 3DCP, but there are also process challenges. The 3D printed 'near-net shape' geometry must be achievable considering the material's manufacturing and rheology constraints, which is required for a very precise control of the geometric quality of the component [61]. The conditions of the material to ensure good printing are challenging, if the trowelling or milling is to be undertaken during the green state then there is an additional time-bound processing window that sits at the far end of the open time of the mortar or concrete. This further constrains scheduling and production.

Milling in the fully hardened state requires more energy and heavier robotic systems [98]. Here, the precision of the mill surface is a function of the toolpath, the shape of the tooling drill and the maximum aggregate size of the concrete, as aggregates can be pulled out during milling [92]. However, with small aggregates typically less than 2 mm, the implications are negligible. Some of the current research questions are around understanding what is possible to manufacture with these processes in terms of size and complexity and, alongside this, understanding of tooling parameters. The benefits of including subtractive processes are feature and surface detail resolution that any other process cannot achieve. The benefits of achievable precision and the resolution of

(a) (b)

Fig. 24. Printing vertically onto a horizontally printed core: a) embedding the robotically fabricated fibre reinforcement; b) robotically trowelling the fresh concrete in a subsequent formative process, [101].

Table 1
List of academic articles with subject focus as they relate to milling of green cement-based materials.

Topic area/insights	Paper References
Demonstration of potential surface finish and feature resolution	[61,89,90,102]
Process insights and observations	[102–105]
Material properties as they relate to the milling process	[98]
Assessment of accuracy and precision benefits	[90,106]
Life Cycle assessment	[107]
Milling of cavities for reinforcement integration	[46]

features are significant [61], enabling the reimagining of what can be manufactured with hybrid systems based on 3DCP [94].

8. Conclusions

This paper provides a systematic overview of the versatility of concrete manufacturing using digital fabrication techniques that go beyond 3DCP with horizontal planar layers. For the Digital 3D Printing processes, the support of the material layers, as well as layer orientation, layer characteristics and layer arrangement were considered for the classification. Accordingly, we categorise four Digital 3D Printing technologies beyond horizontal planar layer printing: (I) Inclined and non-planar layer printing without support, (II) Printing on Core Components, (III) Injection in Carrier Material and (IV) Printing on Formative Substrates. Crucially, to achieve a holistic approach, alongside Digital 3D Printing, we incorporate (V) Digital Casting Systems as well as (VI) Digital Surface Trowelling and Digital Milling processes, showcasing a comprehensive framework for Digital Fabrication with Concrete.

The holistic consideration of these digital fabrication technologies enables the realisation of previously untapped potential in concrete construction, as each technology offers specific benefits.

- Inclined and non-planar 3DCP exemplifies the value of design in sustainable concrete construction through improved functionality, reduced material use, and enhanced visual impact. In structural design, non-planar 3DCP can reduce support material for printing funicular geometries or optimise reinforcement placement between curved layers that align with the force flow. In architectural design, non-planar layers create a distinctive design element, facilitating the assembly of components or producing complex surface textures.
- Printing on Core Components enables increased design freedom for structural efficiency, functional integration, and aesthetic articulation. It has a wide range of applications. These include 3D printing additional structural elements onto existing components using hybrid manufacturing processes, applying plaster to create geometrically complex functional surface structures providing visual, acoustic, or light-diffusing effects, and spraying a cover layer to

Fig. 25. Milling a 3DCP panel to create accurate and precise feature details while the printed material is in its green state (left); and the resulting impact on the aesthetics of the hardened component, partially milled (centre), and fully milled (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structurally embed reinforcement or increase durability, insulation and weather protection. In addition to new construction, the repair and strengthening of existing building structures is a particularly interesting potential for Printing on Core Component techniques.
– Injection in Carrier Material represents a further innovative method for 3D printing concrete structures. In this technique, the material is deposited in a carrier material along unrestricted spatial trajectories, making it ideal for creating intricate structures. Furthermore, when using a hardening carrier material, the technology can combine materials with different properties to realise resource-reduced components.
– Printing on Formative Substrates completes the range of Digital 3D Printing processes. Its particular strength lies in creating highly complex free-form load-bearing structures, where the formwork determines the initial alignment of the layers.
– Digital Casting Systems represent an alternative digital fabrication methodology, where concrete casting is digitally controlled coupled with set-on-demand admixtures to control rheology and hydration, DCS enable the production of structurally optimised components with minimal formwork, material use, and normed reinforcement. Systems like Smart Dynamic Casting have demonstrated high precision in projects such as the SDC Mullions and the Future Tree.
– Finally, Digital Trowelling and Digital Milling processes are of particular interest in the context of hybrid manufacturing processes in combination with Digital 3D Printing techniques. These hybrid processes allow the limitations of 3D Printing, such as precision and surface quality, to be overcome and either improve the component properties or supplement them with additional functions. The integration of formative and subtractive processes within the design-to-fabrication chain is essential for enhancing the application spectrum of digital fabrication in concrete construction.

While these process technologies add a layer of complexity to the design-to-fabrication workflow, they achieve an optimal balance that complements planar 3DCP. The integration of these versatile processes can help overcome the current limitations of digital fabrication in concrete construction. This could be the key to enhancing structural performance, integrating functionality, and achieving design flexibility, leading the way to a sustainable, efficient, and digital future in the construction industry. While first large scale applications have demonstrated the potential of these technologies, several areas still require further research. Key focuses include enhancing the design-to-fabrication workflow, advancements in mixing, especially in the precision and design of inline mixers, process automation, ensuring material robustness, particularly under varying environmental conditions, and reducing the cement content to enhance sustainability.

Abbreviations

3DCP	3D Concrete Printing
ACDC	Admixture Controlled Digital Casting
ARCS	Automated Robotic Concrete Spraying
CiC	Concrete in Concrete (I3DCP variant)
CiS	Concrete in Suspension (I3DCP variant)
DCS	Digital Casting Systems
FDM	Fused Deposition Modelling
I3DCP	Injection 3D Concrete Printing
NGP	Non-Planar Granular Printing
RPS	Robotic Plaster Spraying
SC3DP	Shotcrete 3D Printing
SCC	Self-Compacting Concrete
SDC	Smart Dynamic Casting
SiC	Suspension in Concrete (I3DCP variant)
S-3DCP	Spray-based 3D Concrete Printing
ThinForm	Thin Formworks

CRediT authorship contribution statement

Dirk Lowke: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Conceptualization. **Ana Anton:** Writing – review & editing, Writing – original draft, Visualization. **Richard Buswell:** Writing – original draft, Visualization. **Selen Ercan Jenny:** Writing – review & editing, Writing – original draft, Visualization. **Robert J. Flatt:** Writing – review & editing, Writing – original draft, Visualization. **Ena Lloret Fritschi:** Writing – review & editing, Writing – original draft, Visualization. **Norman Hack:** Writing – review & editing, Writing – original draft, Visualization. **Inka Mai:** Writing – review & editing, Writing – original draft, Visualization. **Mariana Popescu:** Writing – review & editing, Writing – original draft, Visualization. **Harald Kloft:** Writing – review & editing, Writing – original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] J.L. Jewett, J.V. Carstensen, Topology-optimized design, construction and experimental evaluation of concrete beams, Autom. Constr. 102 (2019) 59–67, https://doi.org/10.1016/j.autcon.2019.02.001.
[2] B. García de Soto, I. Agustí-Juan, J. Hunhevicz, S. Joss, K. Graser, G. Habert, B. T. Adey, Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall, Autom. Constr. 92 (2018) 297–311, https://doi.org/10.1016/j.autcon.2018.04.004.
[3] R.A. Buswell, W.R.L. da Silva, F.P. Bos, H.R. Schipper, D. Lowke, N. Hack, H. Kloft, V. Mechtcherine, T. Wangler, N. Roussel, A process classification framework for defining and describing Digital Fabrication with Concrete, Cem. Concr. Res. 134 (2020) 106068, https://doi.org/10.1016/j.cemconres.2020.106068.
[4] R.A. Buswell, F.P. Bos, W.R.L. da Silva, N. Hack, H. Kloft, D. Lowke, N. Freund, A. Fromm, E. Dini, T. Wangler, E. Lloret-Fritschi, R. Schipper, V. Mechtcherine, A. Perrot, K. Vasilic, N. Roussel, Digital Fabrication with Cement-Based Materials: Process Classification and Case Studies, in, 2022, pp. 11–48, https://doi.org/10.1007/978-3-030-90535-4_2.
[5] M. Bi, P. Tran, L. Xia, G. Ma, Y.M. Xie, Topology optimization for 3D concrete printing with various manufacturing constraints, Addit. Manuf. 57 (2022), https://doi.org/10.1016/j.addma.2022.102982.
[6] A. Anton, E. Skevaki, P. Bischof, L. Reiter, B. Dillenburger, Column - slab interfaces for 3D concrete printing: fabrication design and assembly strategies, in: ACADIA 2022, Hybrids & Haecceities, 2022.
[7] J.B. Khurana, S. Dinda, T.W. Simpson, Active - Z Printing: a New Approach to increasing3D Printed Part Strength, in. https://api.semanticscholar.org/CorpusID:204971817, 2020.
[8] A. Anton, A. Yoo, P. Bedarf, L. Reiter, T. Wangler, B. Dillenburger, Vertical modulations:computational design for concrete 3D printed columns, in: ACADIA 2019: Ubiquity and Autonomy 2019, ACADIA, 2019, pp. 596–605.
[9] R.J.M. Wolfs, T.A.M. Salet, N. Roussel, Filament geometry control in extrusion-based additive manufacturing of concrete: the good, the bad and the ugly, Cem. Concr. Res. 150 (2021) 106615, https://doi.org/10.1016/j.cemconres.2021.106615.
[10] L. Reiter, T. Wangler, N. Roussel, R.J. Flatt, The role of early age structural build-up in digital fabrication with concrete, Cem. Concr. Res. (2018), https://doi.org/10.1016/j.cemconres.2018.05.011.

[11] L. Reiter, T. Wangler, A. Anton, R.J. Flatt, Setting on demand for digital concrete: principles, measurements, chemistry and validation, Cem. Concr. Res. 132 (2020) 106047, https://doi.org/10.1016/j.cemconres.2020.106047.
[12] T. Wangler, N. Roussel, F.P. Bos, T.A.M. Salet, R.J. Flatt, Digital concrete: a review, Cem. Concr. Res. 123 (2019) 105780, https://doi.org/10.1016/j.cemconres.2019.105780.
[13] I. Dressler, N. Freund, D. Lowke, The effect of accelerator dosage on fresh concrete properties and on interlayer strength in shotcrete 3D printing, Materials 13 (2020) 374, https://doi.org/10.3390/ma13020374.
[14] S. Bhooshan, A. Dell'Endice, V. Bhooshan, S. Bouten, J. Megens, T. Casucci, H. Lombois-Burger, F. Steiner, T. Van Mele, P. Block, Design, engineering and fabrication of a 3D-concrete-printed unreinforced masonry shell footbridge, in: Proceedings of 5th International Conference on Structures and Architecture - ICSA 2022, 2022.
[15] P. Carneau, R. Mesnil, N. Roussel, O. Baverel, Additive manufacturing of cantilever - from masonry to concrete 3D printing, Autom. Constr. 116 (2020) 103184, https://doi.org/10.1016/j.autcon.2020.103184.
[16] A. Curth, T. Brodesser, L. Sass, C. Mueller, Multi-objective Optimization of 3D Printed Shelltoolpaths, 2021, pp. 1–12.
[17] B. Khoshnevis, Automated construction by contour crafting—related robotics and information technologies, Autom. Constr. 13 (2004) 5–19, https://doi.org/10.1016/j.autcon.2003.08.012.
[18] A. Jipa, A. Anton, L. Gebhard, B. Dillenburger, The Nubian slab: 3D concrete printed stay-in-place formwork for vaulted slabs, in: Digital Concrete 2024, n.d.
[19] Frederic Chovghi, David Richter, Kathrin Dörfler, Pierluigi D'Acunto, Reconsidering the historical cap ceiling: Layerwise form-finding of self-supporting vaulted structures for in situ 3D printing, in: Proceedings of the IASS 2024 Symposium, 2024.
[20] C. Gosselin, R. Duballet, Ph. Roux, N. Gaudillière, J. Dirrenberger, Ph. Morel, Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders, Mater. Des. 100 (2016) 102–109, https://doi.org/10.1016/j.matdes.2016.03.097.
[21] H. Kloft, H.-W. Krauss, N. Hack, E. Herrmann, S. Neudecker, P.A. Varady, D. Lowke, Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP), Cem. Concr. Res. 134 (2020) 106078, https://doi.org/10.1016/j.cemconres.2020.106078.
[22] Hendrik Lindemann, Harald Kloft, Norman Hack, Gradual transition shotcrete 3D printing, in: L. Hesselgren, O.S.H.A. Kilian, S. Malek, K.-G. OlssonC, J.K. Williams (Eds.), Advances in Architectural Geometry 2018, Chalmers University of Technology, Gothenburg, Sweden, 2018.
[23] Norman Hack, Harald Kloft, Dirk Lowke, Additive Fertigung im Bauwesen: 3D-Betondruck als eine Schlüsseltechnologie für die Digitalisierung der Bauwirtschaft, in: Bundesingenieurkammer (Ed.), Ingenieurbaukunst 2020, Ernst & Sohn, 2020.
[24] S. Bhooshan, J. Ladinig, T. Van Mele, P. Block, Function representation for robotic 3D printed concrete, in: robotic fabrication in architecture, Art Des. 2019 (2018) 98–109, https://doi.org/10.1007/978-3-319-92294-2_8.
[25] A. Anton, C.W. Lin, E. Skevaki, M.-Y. Wang, T. Wangler, R.J. Flatt, A. Giraldo Soto, L. Gebhard, W. Kaufmann, M. Hansmeyer, B. Dillenburger, Tor Alva: A 3D concrete printed tower, in: Fabricate 2024: Creating Resourceful Futures, 2024.
[26] H. Kloft, B. Sawicki, F. Bos, R. Dörrie, N. Freund, S. Gantner, L. Gebhard, N. Hack, E. Ivaniuk, J. Kruger, W. Kaufmann, J. Mata-Falcón, V. Mechtcherine, A. Mirjan, R. Wolfs, D. Lowke, Interaction of Reinforcement, Process, and Form in Digital Fabrication with Concrete, Cement and Concrete Research, 2024.
[27] H. Kloft, M. Empelmann, N. Hack, E. Herrmann, D. Lowke, Reinforcement strategies for 3D-concrete-printing, Civil Eng. Des. 2 (2020) 131–139, https://doi.org/10.1002/cend.202000022.
[28] R. Dörrie, N. Freund, E. Herrmann, A. Baghdadi, I. Mai, F. Galli, M. David, K. Dröder, D. Lowke, H. Kloft, Automated force-flow-oriented reinforcement integration for Shotcrete 3D Printing, Autom. Constr. 155 (2023) 105075, https://doi.org/10.1016/j.autcon.2023.105075.
[29] H. Kloft, N. Hack, J. Mainka, L. Brohmann, E. Herrmann, L. Ledderose, D. Lowke, Additive Fertigung im Bauwesen: erste 3-D-gedruckte und bewehrte Betonbauteile im Shotcrete-3-D-Printing-Verfahren (SC3DP), Bautechnik 96 (2019) 929–938, https://doi.org/10.1002/bate.201900094.
[30] S. Ercan Jenny, E. Lloret-Fritschi, D. Jenny, E. Sounigo, P.H. Tsai, F. Gramazio, M. Kohler, Robotic plaster spraying: crafting surfaces with adaptive thin-layer printing, 3D Print Addit. Manuf. 9 (2022) 177–187, https://doi.org/10.1089/3dp.2020.0355.
[31] B. Lu, Z. Li, M. Li, J. Feng, T.N. Wong, S. Qian, Substitution of cement by marine clay in spray-based 3D concrete printing, J. Sustain. Cem.-Based Mater. 13 (2024) 375–388, https://doi.org/10.1080/21650373.2023.2278754.
[32] B. Lu, M. Li, T.N. Wong, S. Qian, Effect of printing parameters on material distribution in spray-based 3D concrete printing (S-3DCP), Autom. Constr. 124 (2021) 103570, https://doi.org/10.1016/J.AUTCON.2021.103570.
[33] R. Dörrie, M. David, N. Freund, D. Lowke, K. Dröder, H. Kloft, In-process integration of reinforcement for construction elements during shotcrete 3D printing, Open Conf. Proc. 3 (2023), https://doi.org/10.52825/ocp.v3i.224.
[34] S. Ercan Jenny, L.L. Pietrasik, E. Sounigo, P.H. Tsai, F. Gramazio, M. Kohler, E. Lloret-Fritschi, M. Hutter, Continuous mobile thin-layer on-site printing, Autom. Constr. 146 (2023) 104634, https://doi.org/10.1016/J.AUTCON.2022.104634.
[35] G.D.S.L.S.E.J.J.P.J.S.L.L.A.R.D.L. Kathrin Dörfler1, Enhancing Construction in Existing Contexts: Opportunities and Challenges in 3D Printing With Mobile Robots for Building Maintenance and Repair, Cem Concr Res, 2024.
[36] K. Dörfler, G. Dielemans, S. Leutenegger, S.J. Ercan, J. Pankert, J. Sustarevas, L. Lachmayer, A. Raatz, D. Lowke, Enhancing construction in existing contexts: opportunities and challenges in 3D printing with mobile robots for building maintenance and repair, in: Digital Concrete 2024, 2024.
[37] N. Hack, I. Dressler, L. Brohmann, S. Gantner, D. Lowke, H. Kloft, Injection 3D concrete printing (I3DCP): basic principles and case studies, Materials 13 (2020), https://doi.org/10.3390/ma13051093.
[38] D. Lowke, A. Vandenberg, A. Pierre, A. Thomas, H. Kloft, N. Hack, Injection 3D concrete printing in a carrier liquid - underlying physics and applications to lightweight space frame structures, Cem. Concr. Compos. 124 (2021) 104169, https://doi.org/10.1016/j.cemconcomp.2021.104169.
[39] N. Hack, H. Kloft, I. Mai, P. D'Acunto, Y. Xiao, D. Lowke, Injection 3D concrete printing: a new approach for lightweight concrete structures, in: Architectural Design (Submitted), 2024.
[40] B. Darweesh, M.P. Gutierrez, S. Schleicher, Non-planar granular 3D printing, construction, Robotics 7 (2023) 291–306, https://doi.org/10.1007/s41693-023-00107-5.
[41] Y. Xiao, N. Khader, A. Vandenberg, D. Lowke, H. Kloft, N. Hack, Injection 3D Concrete Printing (I3DCP) Combined with Vector-Based 3D Graphic Statics, in, 2022, pp. 43–49, https://doi.org/10.1007/978-3-031-06116-5_7.
[42] Soliquid, Large-scale 3D Printing in Suspension. Https://Soliquid.Io/, 2023.
[43] V. Carlota, Soliquid is the startup doing large-scale 3D printing in suspension. Https://Www.3dnatives.Com/En/Soliquid-3d-Printing-Suspension-090720194/, 2019.
[44] I., H. Mai, D. Kloft, A. Lowke, Y. Vandenberg, N. Hack Xiao, Injection 3D concrete printing – exploring new potentials in concrete 3D printing, in: P. Rosendahl, N. Gaudillière-Jami (Eds.), BE-AM: Built Environment Additive Manufacturing, Darmstadt, 2023, pp. 60–71.
[45] P. D'Acunto, J.-P. Jasienski, P.O. Ohlbrock, C. Fivet, J. Schwartz, D. Zastavni, Vector-based 3D graphic statics: a framework for the design of spatial structures based on the relation between form and forces, Int. J. Solids Struct. 167 (2019) 58–70, https://doi.org/10.1016/j.ijsolstr.2019.02.008.
[46] H. Kloft, B. Sawicki, F. Bos, R. Dörrie, N. Freund, S. Gantner, L. Gebhard, N. Hack, E. Ivaniuk, J. Kruger, W. Kaufmann, J. Mata-Falcón, V. Mechtcherine, A. Mirjan, R. Wolfs, D. Lowke, Interaction of reinforcement, process, and form in digital fabrication with concrete, in: Digital Concrete, 2024.
[47] T. Adams, C. Heuer, S. Brell-Cokcan, Dynamic 3D print head for spatial strand extrusion of fiber-reinforced concrete: requirements, development and application, Constr. Robot. 6 (2022) 1–13, https://doi.org/10.1007/s41693-022-00066-3.
[48] A. Jipa, B. Dillenburger, 3D printed formwork for concrete: state-of-the-art, opportunities, challenges, and applications, 3D Print Addit. Manuf. 9 (2022) 84–107, https://doi.org/10.1089/3dp.2021.0024.
[49] M. Nuh, R. Oval, J. Orr, P. Shepherd, Digital fabrication of ribbed concrete shells using automated robotic concrete spraying, Addit. Manuf. 59 (2022) 103159, https://doi.org/10.1016/j.addma.2022.103159.
[50] A. Anton, A. Jipa, L. Reiter, B. Dillenburger, Fast complexity: additive manufacturing for prefabricated concrete slabs, in: RILEM Bookseries, Springer, 2020, pp. 1067–1077, https://doi.org/10.1007/978-3-030-49916-7_102.
[51] S. Lim, R.A. Buswell, P.J. Valentine, D. Piker, S.A. Austin, X. De Kestelier, Modelling curved-layered printing paths for fabricating large-scale construction components, Addit. Manuf. 12 (2016) 216–230, https://doi.org/10.1016/j.addma.2016.06.004.
[52] S. Zivkovic, C. Battaglia, Rough Pass Extrusion Tooling. CNC Post-processing of 3D-printed sub-additive Concrete Lattice Structures, in, 2018, pp. 302–311, https://doi.org/10.52842/conf.acadia.2018.302.
[53] C. Nan, A. Vigorito, Exploring 3D Concrete Printing of Lattice Structures on Robotically-Shaped Sand Formwork for Circular Futures, 2024, pp. 128–135, https://doi.org/10.1007/978-981-97-0621-1_16.
[54] https://adapamoulds.com/references/, 2024.
[55] H.R. Schipper, Double-curved precast concrete elements, in: Research Into Technical Viability of the Flexible Mould Method, TU Delft, 2015.
[56] C. Borg Costanzi, Z.Y. Ahmed, H.R. Schipper, F.P. Bos, U. Knaack, R.J.M. Wolfs, 3D printing concrete on temporary surfaces: the design and fabrication of a concrete shell structure, Autom. Constr. 94 (2018) 395–404, https://doi.org/10.1016/j.autcon.2018.06.013.
[57] W.J. Hawkins, M. Herrmann, T.J. Ibell, B. Kromoser, A. Michaelski, J.J. Orr, R. Pedreschi, A. Pronk, H.R. Schipper, P. Shepherd, D. Veenendaal, R. Wansdronk, M. West, Flexible formwork technologies – a state of the art review, Struct. Concr. 17 (2016) 911–935, https://doi.org/10.1002/suco.201600117.
[58] D. Veenendaal, M. West, P. Block, History and overview of fabric formwork: using fabrics for concrete casting, Struct. Concr. 12 (2011) 164–177, https://doi.org/10.1002/suco.201100014.
[59] T. Méndez Echenagucia, D. Pigram, A. Liew, T. Van Mele, P. Block, A cable-net and fabric formwork system for the construction of concrete shells: design, fabrication and construction of a full scale prototype, Structures 18 (2019) 72–82, https://doi.org/10.1016/j.istruc.2018.10.004.
[60] M. Popescu, M. Rippmann, A. Liew, L. Reiter, R.J. Flatt, T. Van Mele, P. Block, Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell, Structures 31 (2021) 1287–1299, https://doi.org/10.1016/j.istruc.2020.02.013.
[61] P. Rennen, S. Gantner, G. Dielemans, L. Bleker, N. Christidi, R. Dörrie, M. Hojjat, I. Mai, K. Mawas, D. Lowke, P. D'Acunto, K. Dörfler, N. Hack, M. Popescu, Robotic knitcrete: computational design and fabrication of a pedestrian bridge

using robotic shotcrete on a 3D-knitted formwork, Front. Built Environ. 9 (2023), https://doi.org/10.3389/fbuil.2023.1269000.

[62] P. Ayres, W.R. Leal da Silva, P. Nicholas, T.J. Andersen, J.P.R. Greisen, SCRIM – sparse concrete reinforcement in Meshworks, in: Robotic Fabrication in Architecture, Art and Design 2018, Springer International Publishing, Cham, 2019, pp. 207–220, https://doi.org/10.1007/978-3-319-92294-2_16.

[63] N. Taha, A.N. Walzer, J. Ruangjun, Robotic AeroCrete a Novel Robotic Spraying and Surface Treatment Technology for the Production of Slender Reinforced Concrete Elements, in: Blucher Design Proceedings, Editora Blucher, São Paulo, 2019, pp. 245–256, https://doi.org/10.5151/proceedings-ecaadesigradi2019_675.

[64] D. Marchon, S. Kawashima, H. Bessaies-Bey, S. Mantellato, S. Ng, Hydration and rheology control of concrete for digital fabrication: potential admixtures and cement chemistry, Cem. Concr. Res. 112 (2018) 96–110, https://doi.org/10.1016/j.cemconres.2018.05.014.

[65] E. Lloret, A.R. Shahab, M. Linus, R.J. Flatt, F. Gramazio, M. Kohler, S. Langenberg, Complex Concrete Structures: Merging Existing Casting Techniques With Digital Fabrication, 60 (n.d.) 40–49. doi:https://doi.org/10.1016/j.cad.2014.02.011.

[66] L. Reiter, T. Wangler, A. Anton, R.J. Flatt, Setting on Demand for Digital Concrete – Principles, Measurements, Chemistry, Validation, 132 (n.d.) 106047. doi: https://doi.org/10.1016/j.cemconres.2020.106047.

[67] E. Lloret Fritschi, Smart Dynamic Casting - A Digital Fabrication Method For non-standard Concrete Structures, (n.d.). doi:https://doi.org/10.3929/ethz-a-010800371.

[68] J.J. Burger, E. Lloret-Fritschi, F. Scotto, T. Demoulin, L. Gebhard, J. Mata Falcón, F. Gramazio, M. Kohler, R.J. Flatt, Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures, 7 (n.d.) 48–59. doi:https://doi.org/10.3929/ethz-b-000410523.

[69] A. Szabo, L. Reiter, E. Lloret-Fritschi, T. Wangler, F. Gramazio, M. Kohler, R.J. Flatt, ACDC: the admixture controlled digital casting and its application to thin folded concrete structures, in: Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 2, Springer International Publishing, n.d.: pp. 956–966.

[70] E. Lloret-Fritschi, J. Choma, F. Scotto, A. Szabo, F. Gramazio, M. Kohler, R. J. Flatt, In-crease: less concrete more paper, RILEM Techn. Lett. 7 (2023) 199–208, https://doi.org/10.21809/rilemtechlett.2022.168.

[71] L. Reiter, T. Wangler, N. Roussel, R.J. Flatt, The Role of Early Age Structural Build-up in Digital Fabrication With Concrete, 112 (n.d.) 86–95. doi:https://doi.org/10.1016/j.cemconres.2018.05.011.

[72] L. Reiter, The Underlying Physics and Chemistry of Digital Fabrication with Concrete – Controlling and Monitoring Structural Build-up, (n.d.).

[73] T. Wangler, Digital concrete processing: a review, in: Proceedings of the 1st International Conference on 3D Construction Printing (3DcP 2018), n.d. doi: https://doi.org/10.3929/ethz-b-000309847.

[74] A.R. Shahab, E. Lloret Kristensen, P. Fischer, F. Gramazio, M. Kohler, R.J. Flatt, Smart dynamic casting or how to exploit the liquid to solid transition in cementitious materials, in: 7th RILEM International Conference on Self-Compacting Concrete and 1st RILEM International Conference on Rheology and Processing of Construction Materials, n.d.

[75] F. Gramazio, M. Kohler, R. Flatt, E.L. Kristensen, Apparatus and Method for Vertical Slip Forming of Concrete Structures, (n.d.). https://patents.google.com/patent/WO2014121917A1/en.

[76] E. Lloret-Fritschi, F. Scotto, F. Gramazio, M. Kohler, K. Graser, T. Wangler, L. Reiter, R.J. Flatt, J. Mata-Falcón, Challenges of real-scale production with smart dynamic casting, in: T. Wangler, R.J. Flatt (Eds.), First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018, Springer International Publishing, n.d.: pp. 299–310.

[77] NCCR DFAB, Smart Dynamic Casting – DFAB House, (n.d.). https://dfabhouse.ch/de/smart-dynamic-casting/.

[78] A. Szabo, L. Reiter, E. Lloret-Fritschi, F. Gramazio, M. Kohler, R.J. Flatt, Mastering Yield Stress Evolution and Formwork Friction for Smart Dynamic Casting, 13 (n.d.) 2084. doi:https://doi.org/10.3929/ethz-b-000418038.

[79] M. Schultheiss, T. Wangler, L. Reiter, N. Roussel, R.J. Flatt, Feedback control of smart dynamic casting through formwork friction measurements, in: Flowing Toward Sustainability, n.d.

[80] K. Graser, M. Baur, A.A. Apolinarska, K. Dörfler, N. Hack, A. Jipa, E. Lloret-Fritschi, T. Sandy, D. Sanz-Pont, D. Hall, M. Kohler, DFAB House: a comprehensive demonstrator of digital fabrication in architecture, in: J. Burry, J. Sabin, B. Sheil, M. Skavara (Eds.), Fabricate 2020: Making Resilient Architecture, UCL Press, n.d.: pp. 130 – 140. doi:https://doi.org/10.3929/ethz-b-000447227.

[81] Basler & Hofmann AG, The “Future Tree”: a pilot project for parametric planning, Reportage GHA Future Tree Basler & Hofmann (n.d.). https://www.baslerhofmann.ch/en/news/reportage-gha-fututre-tree.html (accessed April 7, 2024).

[82] J. Burger, P. Aejmelaeus-Lindström, S. Gürel, F. Niketić, E. Lloret-Fritschi, R.J. Flatt, F. Gramazio, M. Kohler, Eggshell Pavilion: a Reinforced Concrete Structure Fabricated Using Robotically 3D Printed Formwork, (n.d.) 1–21.

[83] J. Burger, E. Lloret-Fritschi, M. Akermann, D. Schwendemann, F. Gramazio, M. Kohler, Circular Formwork: Recycling of 3D Printed Thermoplastic Formwork for Concrete, 7 (n.d.) 204–215. doi:https://doi.org/10.1080/24751448.2023.2245724.

[84] J.J. Burger, T. Huber, J. Mata Falcón, E. Lloret-Fritschi, W. Kaufmann, F. Gramazio, M. Kohler, Design, fabrication, and testing of an optimised reinforced concrete floor slab fabricated with robotically 3D printed formwork, in: 3rd RILEM International Conference on Concrete and Digital Fabrication (Digital Concrete 2022), n.d.

[85] A. Szabo, Design and Fabrication of Thin Folded Members with Digital Concrete Processes, 2020, https://doi.org/10.3929/ETHZ-B-000453808.

[86] Mackenzie, Goldberg, Joseph Choma Explains Why Folding Is Important to the Field of Architecture, (n.d.). https://archinect.com/news/article/150135426/joseph-choma-explains-why-folding-is-important-to-the-field-of-architecture.

[87] E. Lloret-Fritschi, J. Choma, F. Scotto, A. Szabo, F. Gramazio, M. Kohler, R.J. Flatt, In-Crease: Less Concrete More Paper, 7 (n.d.) 199–208.

[88] E. Lloret-Fritschi, E. Quadranti, F. Scotto, L. Fuhrimann, T. Demoulin, S. Mantellato, L. Unteregger, J. Burger, R.G. Pileggi, F. Gramazio, M. Kohler, R. J. Flatt, Additive digital casting: from lab to industry, Materials 15 (2022) 3468, https://doi.org/10.3390/ma15103468.

[89] P. Rennen, N. Khader, N. Hack, H. Kloft, A hybrid fabrication approach for a functionally integrated loadbearing concrete panel system: combining additive manufacturing and green state concrete cutting, in: B. Farahi, B. Bogosian, J.L. G. del Castillo y Lopez, K. Dörfler, S. Parascho, V.A.A. Noel (Eds.), ACADIA2021 Realignments: Toward Critical Computation, The Association for Computer Aided Design in Architecture, 2021.

[90] R. Buswell, J. Xu, D. De Becker, J. Dobrzanski, J. Provis, J.T. Kolawole, P. Kinnell, Geometric quality assurance for 3D concrete printing and hybrid construction manufacturing using a standardised test part for benchmarking capability, Cem. Concr. Res. 156 (2022) 106773, https://doi.org/10.1016/j.cemconres.2022.106773.

[91] N. Hack, H. Kloft, Shotcrete 3D Printing technology for the fabrication of slender fully reinforced freeform concrete elements with high surface quality: a real-scale demonstrator, in: T.A.M. Salet, F.P. Bos, R. Wolfs (Eds.), 2nd RILEM International Conference on Concrete and Digital Fabrication, Rilem Publications, Eindhoven, 2020.

[92] J. Bard, D. Cupkova, N. Washburn, G. Zeglin, Robotic concrete surface finishing: a moldless approach to creating thermally tuned surface geometry for architectural building components using Profile-3D-Printing, Constr. Robot. 2 (2018) 53–65, https://doi.org/10.1007/s41693-018-0014-x.

[93] N. Hack, H. Kloft, Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator, 2020, pp. 1128–1137, https://doi.org/10.1007/978-3-030-49916-7_107.

[94] S. Gantner, P. Rennen, T. Rothe, C. Hühne, N. Hack, Core Winding: Force-Flow Oriented Fibre Reinforcement in Additive Manufacturing with Concrete, 2022, pp. 391–396, https://doi.org/10.1007/978-3-031-06116-5_58.

[95] N. Kepczak, P. Zgorniak, P. Lajmert, R. Rosik, M. Sikora, Influence of machining parameters on the polymer concrete milling process, Int. J. Adv. Manuf. Technol. 106 (2020) 3017–3032, https://doi.org/10.1007/s00170-019-04811-x.

[96] I. Mai, L. Brohmann, N. Freund, S. Gantner, H. Kloft, D. Lowke, N. Hack, Large particle 3D concrete printing—a green and viable solution, Materials 14 (2021) 6125, https://doi.org/10.3390/ma14206125.

[97] A. Baghdadi, L. Ledderose, S. Ameri, H. Kloft, Experimental and numerical assessments of new concrete dry connections concerning potentials of robotic CNC manufacturing technique, Eng. Struct. 280 (2023) 115605, https://doi.org/10.1016/j.engstruct.2023.115605.

[98] J. Dobrzanski, R. Buswell, S. Cavalaro, P. Kinnell, W. Wang, J. Xu, J. Kolawole, Milling a cement-based 3D printable mortar in its green state using a ball-nosed cutter, Cem. Concr. Compos. 125 (2022) 104266, https://doi.org/10.1016/j.cemconcomp.2021.104266.

[99] J. Bard, A. Bidgoli, W.W. Chi, Image classification for robotic plastering with convolutional neural network, in: Robotic Fabrication in Architecture, Art and Design 2018, Springer International Publishing, Cham, 2019, pp. 3–15, https://doi.org/10.1007/978-3-319-92294-2_1.

[100] N. Hack, H. Kloft, Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator, 2020, pp. 1128–1137, https://doi.org/10.1007/978-3-030-49916-7_107.

[101] S. Gantner, P. Rennen, T. Rothe, C. Hühne, N. Hack, Core Winding: Force-Flow Oriented Fibre Reinforcement in Additive Manufacturing with Concrete, 2022, pp. 391–396, https://doi.org/10.1007/978-3-031-06116-5_58.

[102] J. Canou, M. Uhart, P. Diaz, A “low-cost” subtractive method for freshly finished 3D concrete printed structures, Proc. Comput. Sci. 180 (2021) 32–39, https://doi.org/10.1016/j.procs.2021.01.125.

[103] M. Popescu, KnitCrete: Stay-in-Place Knitted Fabric Formwork for Complex Concrete Structures, ETH Zurich, Department of Architecture, 2019.

[104] J. Xu, J.T. Kolawole, J. Provis, J. Dobrzanski, P. Kinnell, S. Cavalaro, W. Wang, R. Buswell, An Early Trial on Milling 3D Printed Concrete Geometries: Observations and Insights of the Process, 2022, pp. 9–14, https://doi.org/10.1007/978-3-031-06116-5_2.

[105] P. Kinnell, J. Dobranski, J. Xu, W. Wang, J. Kolawole, J. Hodgson, S. Austin, J. Provis, S. Pialarissi-Cavalaro, R. Buswell, Precision Manufacture of Concrete Parts Using Integrated Robotic 3D Printing and Milling, 2021 (/articles/conference_contribution/Precision_manufacture_of_concrete_parts_using_integrated_robotic_3D_printing_and_milling/14994456/1 (accessed April 9, 2024)).

[106] N. Hack, C. Jantzen, L. Brohmann, M. Gerke, K. Mawas, M. Maboudi, A Closed-Loop Workflow for Quality Inspection and Integrated Post-processing of 3D-Printed Concrete Elements, 2022, pp. 364–369, https://doi.org/10.1007/978-3-031-06116-5_54.

[107] I. Muñoz, J. Alonso-Madrid, M. Menéndez-Muñiz, M. Uhart, J. Canou, C. Martin, M. Fabritius, L. Calvo, L. Poudelet, R. Cardona, H. Lombois-Burger, N. Vlasopoulos, C. Bouyssou, J. Dirrenberger, A. Papacharalampopoulos, P. Stavropoulos, Life cycle assessment of integrated additive–subtractive concrete

3D printing, Int. J. Adv. Manuf. Technol. 112 (2021) 2149–2159, https://doi.org/10.1007/s00170-020-06487-0.