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Integration of Discrete Reinforcement Elements for Shotcrete 3D Printing of Complex Structures

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Abstract. By applying the material layer by layer, Additive Manufacturing (AM) in construction eliminates the need for conventional formwork and allows for the fabrication of architecturally expressive designs as well as material-efficient geometries derived from structural optimisation algorithms. To date, the fundamentals of material application within the AM process has already been researched extensively. However, the integration of reinforcements into additively manufactured concrete remains a major challenge, especially with regard to embedding the reinforcements into highly complex and topology-optimised forms aligning with the resulting force-flow.

With this background, this study explores three discrete-element-based reinforcement techniques tailored to the requirements of Shotcrete 3D Printing to enable continuous reinforcement within complex geometries: short rebar insertion, where straight rebars are inserted across the layer structure to form continuous vertical reinforcement by slight overlapping. 3D short rebar joining is a possible alternative, straight rebars are joint by welding in the force-flow direction. And finally, 3D bent rebar joining, where short rebars, pre-bent according to the force-flow, are joint by welding into a continuous structure.

Each technique is discussed individually in terms of the process adaptability, process limitations and individual joining techniques based on the defined criteria. Additionally, a full-scale test during printing is performed to qualitatively evaluate the processes and respective limitations. A comparison reveals respective advantages and identifies potential combinations for complex printed geometries. On this basis, future research topics are enabled, such as force-flow oriented reinforcement layouts and their automated manufacturing methods to pave the way for the application as material-efficient and structurally optimised elements in the construction industry.

Keywords: Shotcrete 3D Printing, Reinforcement, Additive Manufacturing, Robotic Fabrication, Automation

1. Introduction

In the last decades, the importance of automation in the construction industry increased drastically. The motivation are cost reductions, shortages of skilled labour [1] and desired reductions of health issues [2]. A special interest for solving this challenge is seen in Additive Manufacturing (AM). For example, prior to 2010 less than 30 publications regarding concrete 3D printing were published, as of 2021 the amount surpassed 450. This results from different research centres and companies working towards implementing various AM-process into digital workflows for the construction industry [3]. Especially for complex shaped elements AM processes have demonstrated possibilities for the reduction of production costs in comparison to the same geometry built with traditional building techniques [4].

Currently three different AM processes are established within the state of the art: binder jetting, extrusion and material jetting, each with individual advantages and disadvantages [5]. The main differences can be summarised in an ambiguous relation of production time, geometrical accuracy and potential for the integration of reinforcement. Material jetting processes such as Shotcrete 3D Printing (SC3DP) offer the advantage of higher nozzle-to-strand distances improving the potential for reinforcement integrations for both straight or pre-bent rebars [6,7].

Nevertheless, the integration of reinforcements remains a big challenge in AM. The reinforcements are usually straight rebars placed between layers or penetrating various layers [8]. Through the combination of digital design and integrated structural analysis AM has the potential to significantly reduce the required reinforcement. For complex force-flow trajectories, the reinforcement integration process has to be adapted. This article proposes a concept for complex reinforcement integration considering the connection of segmented rebars to establish force-flow aligned continuous reinforcement for AM processes.

2. State of the art

The following chapter presents the state of the art of force-flow oriented reinforced elements and joining discrete reinforcements.

An overview of possible reinforcement strategies for AM is given in [9]. The reinforcement techniques can be generally categorised based on the forming material. Either the applied concrete shapes the element and influences the reinforcement technique (concrete supports reinforcement) or a prefabricated reinforcement structure can be encased by an AM process (reinforcement supports concrete). Furthermore, the techniques are divided in single step and two step processes. Within the concept of single step processes the focus is set across layer integration in this study. Preliminary work exhibited the potential and adaptability of this approach [6,10–12].

This study aims to expand this overview in [9] by presenting a concept for multidimensional reinforcement composition in a sequential AM process. This allows for material efficient reinforcement structures by following complex force-flow trajectories.

2.1 Joining methods for steel reinforcement elements

Dividing the reinforcement structures into segments is often a necessary step due to manufacturing constraints or the desire to utilise cost-effective standardised rebar. This segmentation requires an effective joining of individual rebars to ensure sufficient load capacities. In the context of construction, the DIN EN 1992-1-1 describes the methods for joining metal rebars. The processes conventionally involve welding, hook joints or mechanical coupling [13]. Dörrie et al. describe an approach for in-process integration and joining for SC3DP by creating an overlap joint inside the printed concrete [6]. This only allows for straight reinforcement structures. An automated resistance welding approach involves joining short, straight rebar elements, which are then filled with concrete [14,15]. With this process it is possible to approximate curved structures, as short reinforcements can be joined at an angle. A stud welding approach is utilised by Claßen et al. [16]. The reinforcement structure is manufactured by joining rebar through a butt connection into a continuous structure in a sequential process with the additive application of concrete. The concrete is extruded around the reinforcements with a fork shaped nozzle. This only allows for rebar structures central and parallel to the concrete strand. Khoshnevis employs a method with interlocking reinforcement elements, enabling an approach without introducing heat [17]. This process requires specialised reinforcement elements to enable load bearing joints. Another approach presents an automated fabrication process of double curved reinforcement structures, which includes the automated bending of rebar and binding for conventional concrete casting [18]. Momeni et al. is using a cell with multiple robots for assembling a rebar cage by joining rebar elements through a binding process [19]. However, this method only ensures positioning and orientation alignment of the rebars, as load-bearing capabilities of the joints are not attainable. Chen et. al. present a method for sequential build-up of a reinforcement structure using a mortise-and-tenon joint [20]. This method shows the efficacy of a sequential printing and reinforcement process but only allows for straight rebar structures.

2.2 Force-flow based optimisation for reinforced concrete elements

The main advantages of AM for construction are possibilities for faster fabrication times, reduced manual labour as well as higher precision due to robotic fabrication [21–23]. Furthermore, there is large potential for peripheral processes such as aligning reinforcements with the force-flow, increasing efficiency for time, costs and material [15,24–26]. Previous research has already introduced a workflow to analyse beam type elements and manufacture reinforcement according to the resulting load paths [27]. The results of testing the reinforcement demonstrated an increase of flexural strength up to 60 % or material savings up to 60 % with a comparable load bearing capacity. Furthermore, approaches have been evaluated to combine the robotic path planning during printing with the analysed force-flow to integrate optimised reinforcement structures [28], [29]. The resulting beam structures visualise the achievable complexity utilising AM. Asprone et. al. utilised a more mechanically oriented approach by separating pressure and tension members while arranging each element according to the analysed load paths [30]. To save material and increase the efficiency of slab-like elements, similar approaches can be utilised. Recent work has focussed on realising large scale structures with force-flow aligned printing paths and reinforcement integration [31–33]. Additionally, Gantner et. al. explored the approach of force-flow aligned reinforcement for wall type elements [34]. Reinforcement fibres were placed along the load paths on the printed structure and encased by a cover layer. Similarly, the integration of discrete rebar elements aligned with the force-flow has been shown to reinforce a wall and column element [10]. However, research on continuous reinforcement structures embedded in the printed element as parallel process are still scarce.

3. Concept for force-flow oriented reinforcement based on discrete elements

The internal force-flow of a structure varies depending on its geometry and load case, leading to a range of reinforcement trajectories. Segmenting reinforcements into discrete elements offers a viable strategy to align with these trajectories, particularly when integrating vertical reinforcements in layered additive manufacturing processes such as SC3DP. *Figure 2* illustrates three reinforcement concepts using discrete elements, each offering different levels of force-flow approximation and integration complexity.

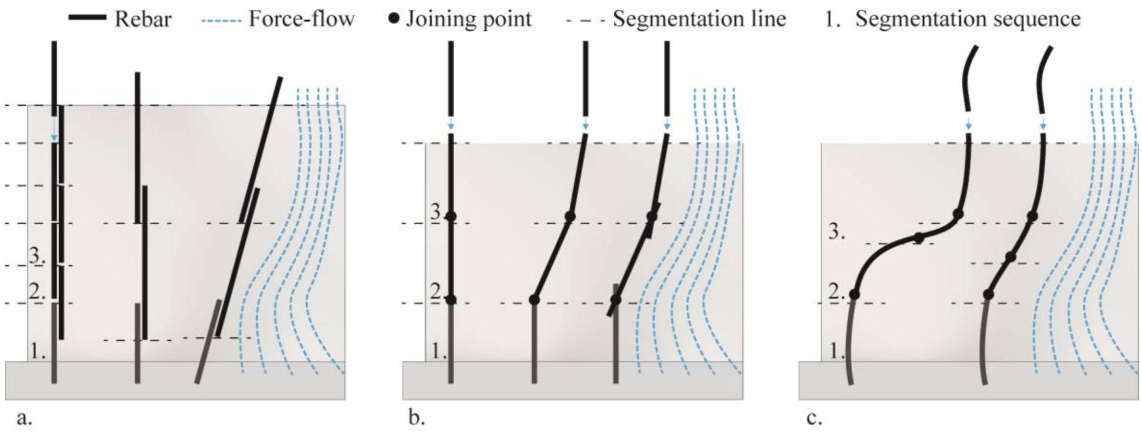


Figure 1. *Reinforcement methods utilising discrete elements; a. Straight rebar insertion; b. Straight rebar joining; c. Bent rebar joining*

Each technique can be utilised by implementing a connection reinforcement at the beginning of the printing process at the base of the structure. The print encases the reinforcements and leaves the joining points uncovered to add the next section of the continuous reinforcement structure. After adding the subsequent section, another print segment can be applied encasing the reinforcement. This sequential process enables the construction of a spatial reinforcement structure embedded within the printed element and aligned with the force-flow.

When utilising straight rebars, overlapping within the printing sections can be used to create a continuous vertical structure, see Figure 1a. This approach is limited by the linear nature of the bars and requires significant overlaps to ensure structural continuity, allowing only unidirectional extensions. While tilting the bars may approximate curved force-flows, geometric possibilities remain limited. The same restrictions apply for longer rebars, but the print sections can be enlarged and the process speed increased. Due to fewer printing interruptions and shorter overall integration times, the printing time can be reduced; however, this results in compromises regarding the adaption to the force-flow.

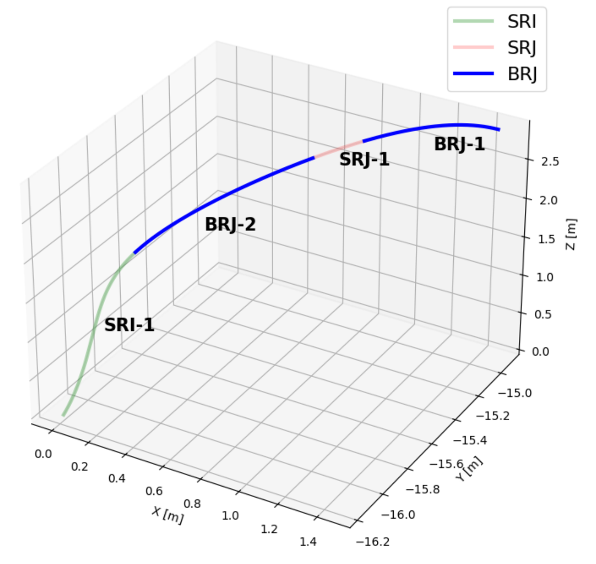
By Straight Rebar Joining (SRJ), the flexibility can be improved and a better approximation towards the force-flow can be achieved, see Figure 1b. Due to joining of the rebars shortly above the printed section, an angle can be applied. The force-flow can be approximated in multiple appended straight sections. The maximum rebar length is constrained by the spray distance of the SC3DP process and the required protruding length of the previous rebar. However, the joining interface must be carefully prepared after the printing step, as previous print layers may leave residual concrete with large influences on the bonding capabilities. The height of the printing segments therefore has to be aligned with the nozzle distance.

The most accurate alignment can be achieved by using Bent Rebar Joining (BRJ), which is achieved by segmenting bent rebars along the force-flow trajectory, see *Figure 1*c. These elements are placed incrementally above the printed section and joined to reconstruct the 3D path. The force-flow aligned rebar can be segmented using an algorithm to segment a 3D line into 2D sections. Subsequently they are joint and built into the 3D structure during the printing process. The segment height is constrained by the nozzle distance and the segmentation logic, considering the segment height. Similar to the previous method, joining surfaces must be clean to ensure a secure connection. The process requires both cutting the rebar to the required length and bending it to replicate segments of the force-flow, minimising stress peaks due to discontinuous rebar structures. When integrating these elements, the print strategy has to be adjusted according to the segment height the algorithm calculated.

In general, a close interaction between the print strategy planning and the reinforcement integration is of key relevance when utilising the concepts.

For an effective process planning, it is crucial to establish a prioritisation for the reinforcement techniques and an appropriate segmentation strategy for minimising labour-intensive steps, such as cutting or complex bending. Maximising the use of longer rebar lengths can significantly reduce the production time. The proposed segmentation strategy employed aims to decompose complex force-flows into discrete rebar elements according to the reinforcement techniques.

Table 1. *Dimensions, their corresponding physical representation and an exemplary segmentation of a force-flow trajectory*

<table>
<tr><th>Dimension</th><th>Physical representation</th><th>Segmentation of a force-flow trajectory</th></tr>
<tr><td>S</td><td>Segment</td><td rowspan="10">
</td></tr>
<tr><td>t</td><td>Arc length of force-flow trajectory</td></tr>
<tr><td>$\kappa(t)$</td><td>Curvature of the trajectory</td></tr>
<tr><td>$\kappa_{threshold}$</td><td>Threshold of curvature values</td></tr>
<tr><td>l_{Sz}</td><td>Length of the segment in the z-direction</td></tr>
<tr><td>d_{spray}</td><td>Distance of nozzle to printed strand</td></tr>
<tr><td>l_{pz}</td><td>Protruding length of previous rebar in z-direction</td></tr>
<tr><td>l_{min}</td><td>Minimum length of rebar</td></tr>
<tr><td>$d_{toplane}$</td><td>Distance to spanned plane</td></tr>
<tr><td>$d_{threshold}$</td><td>Threshold of distance to the plane</td></tr>
</table>

Within this context, an algorithmic approach for the reinforcement process planning process is proposed. By utilising the prioritisation for minimising individual rebar preparation operations, a given force-flow can be segmented into process-specific segments. The structural analysis of a construction element provides force-flow trajectories $\boldsymbol{r}(\boldsymbol{t})$. Afterwards, the scalar curvature κ for a three-dimensional trajectory is calculated as a function of the arc length t.

$$\kappa(t) = \frac{\left\| \dot{\boldsymbol{r}}(\boldsymbol{t}) \times \ddot{\boldsymbol{r}}(\boldsymbol{t}) \right\|}{\left\| \dot{\boldsymbol{r}}(\boldsymbol{t}) \right\|^3}$$

Table 1 presents the used dimensions and their representation. A segment S of the force-flow trajectory is considered and checked, whether its z component conforms to $l_{Sz} \geq d_{spray} - l_{pz}$ with $\forall t \in S\ \kappa(t) \leq \kappa_{threshold}$. In such scenario, it is regarded as a reinforcement as in *Figure 1*a. If its z component is $l_{min} \leq l_{pz} \leq d_{spray} - l_{pz}$ and $\forall t \in S\ \kappa(t) \leq \kappa_{threshold}$, it is conforming to *Figure 1*b. l_{min} is the minimum length of a rebar segment to be viable for the joining process. A shorter rebar cannot be handled and joined sufficiently. The parameter l_{pz} can be adjusted to comply with requirements posed by the joining process and its influence on the concrete. For joining processes with high heat input into the rebar, l_{pz} can be increased to limit the conducted heat into the already printed concrete. The segments left of the force-flow conform to $l_{min} \leq l_{pz} \leq d_{spray} - l_{pz}$ with a curvature of $\forall t \in S\ \kappa(t) > \kappa_{threshold}$. Therefore, the rest of the trajectory is categorised as in *Figure 1*c. Moreover, these segments are divided into two-dimensional segments. Taking three discrete points of a three-dimensional segment of the force-flow trajectory, a plane can be spanned. The additional points of the trajectory can be analysed for their distance normal to that plane $d_{toplane}$. If the distance $\forall t \in S\ d_{toplane}(t) > d_{threshold}$, a new segment is being started.

4. Prototypical manufacturing case study

The following chapter describes the full-scale test for the qualitative evaluation of the developed concepts. A structurally complex building section was designed and analysed regarding the possible loadbearing capacity. The section comprises a pronounced cantilever of a loadbearing wall section. The wall element has to transfer the load into the ground floor. The resulting complex force-flow cannot be efficiently depicted by a traditional rebar cage.

4.1 Experimental setup and methods

As a basis for the experiments, the building section was analysed utilising digital tools to visualise the force-flow and incurred it into a reinforcement layout. For the simplified approach Karamba 3d was utilised to show the displacement, principal stresses and force-flow lines [35]. *Figure 2* visualises the four steps of the analysis and the selected section for testing. The force-flow in the selected section displays a double curved line. To integrate the reinforcement, a segmentation into discrete element has to be carried out.

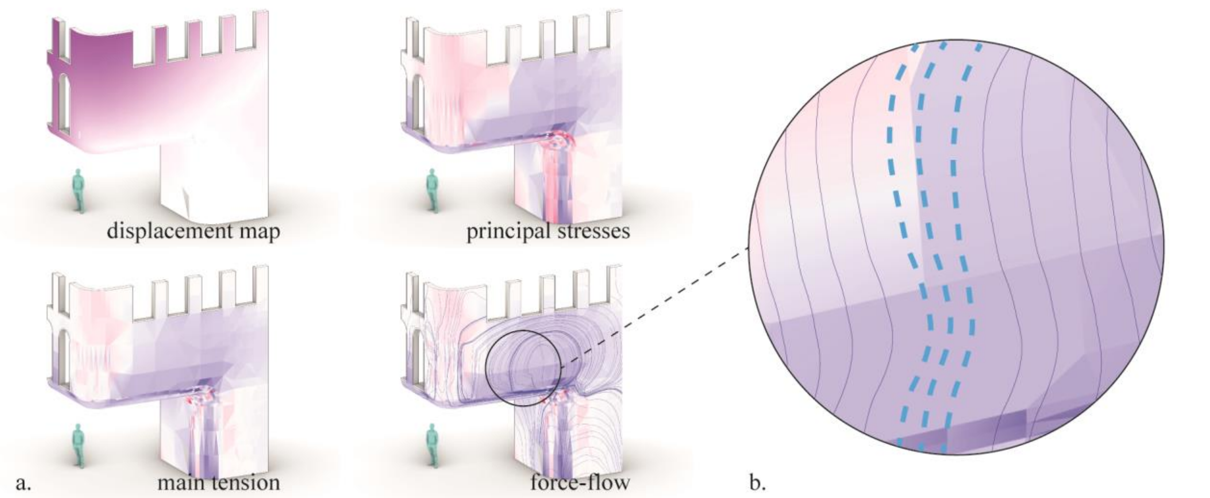


Figure 2. *Exemplary building section; a. displacement map, principal stresses, tensions stresses, tensions stresses as force-flow; b. selected section for 1:1 scale test*

For the purpose of this study, the reinforcement processes from *Figure 1*b and c are tested. The process from *Figure 1*a is described in detail by Dörrie et. al. [6]. The force-flow trajectory depicted in *Figure 2*b is constructed using the SRJ and BRJ process. The segmentation process entails the division of the trajectory into elements along the height of the structure. The 8 mm in diameter rebar segments are manually cut to the required length and subsequently bent into shape in accordance with the force-flow specifications. The process of joining is achieved through the implementation of manual wire arc welding realising a butt joint.

The manufacturing of the reinforced element is executed through the SC3DP process at the Digital Building Manufacturing Laboratory (DBFL) at TU Braunschweig [36,37]. The SC3DP process was performed with a traverse speed of 4500 mm/min, a nozzle distance of 200 mm, an air volume flow of 40 m^3/h and a concrete volume flow of 0.4 m^3/h. This resulted in a planned wall width of 120 mm allowing a sufficient concrete cover of the rebar on both sides when placed in the centre of the element. As printing material, a commercially available fine-grained concrete (MC Bauchemie Nafufill KM 250) with a maximum grain size of 2 mm is used.

In conjunction with the joining processes, the thermal output resulting from the welding process is monitored on a macro scale with an infrared camera Optris PI 640i to observe trends of heat distribution.

4.2 Investigation and results

The experiments demonstrated promising results regarding the manufacturability of force-flow aligned reinforcement structures from discrete elements during the printing process. The selected element was segmented into four sections of 15 cm in height each. Alternating with the printing process the reinforcement was added after each segment. During the joining process, the robot is in a waiting position for approx. four minutes to allow for the welding process to be executed. Afterwards, the printing is continued for minimising production time therefore emphasising the effect of spraying on rebars with increased temperature.

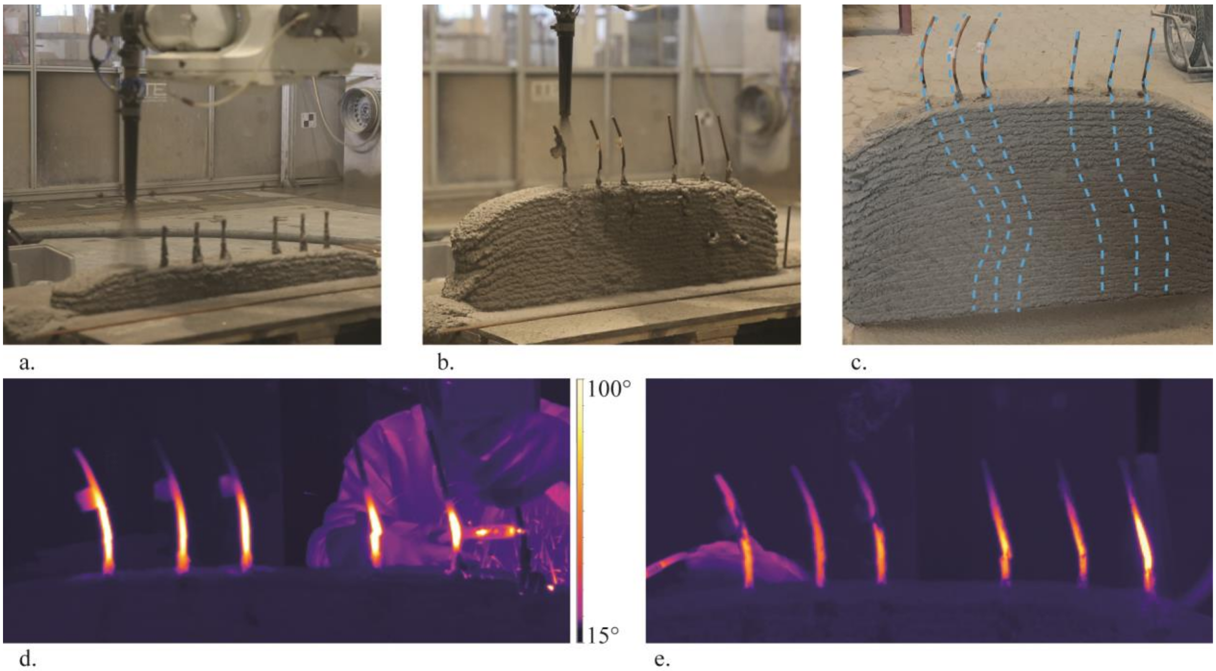


Figure 3. *a. first segment printed on connection reinforcement; b. second segment after joining the third layer of reinforcement; c. finished element overlaid with analysed force-flow from Figure 2 b; d. thermal imaging of welding process; e. thermal imaging of SC3DP on previously welded rebar.*

The welding process was carried out manually. A butt joint configuration was employed to join the components. Prior to the process, it was necessary to clean the joining point after printing each segment and encasing the previous rebar in concrete. The utilisation of pressurised air ensured the effective removal of residual concrete, thereby facilitating a clean connection for the subsequent welding process. The infrared camera revealed high temperatures within the rebar towards the concrete surface heating up the surrounding material. The rebar temperature at the joining point increased to significantly higher than 100°C, therefore forcing water to evaporate, when spraying with wet mix concrete.

4.3 Discussion

By segmenting the reinforcement and adjusting the print strategy to achieve a subsequent build-up of concrete and reinforcement, complex structures can be achieved. While the concepts proved to be viable solutions, various challenges were observed during testing.

According to the print strategy, it is of high importance to leave a sufficient joining point uncovered by concrete to add the next section. In this study, 8 mm rebar was selected due to its suitability for manual bending. According to DIN EN 1992-1-1, steel rebar must be at least 20 mm in diameter to fabricate butt joints via welding [13]. Consequently, rebar used in this context would have necessitated the implementation of an overlapping joint. Such overlapping joints would necessitate extended lengths of protruding rebar to ensure the structural integrity of the reinforcement structure.

The joining points have to be cleaned before joining. Due to the residue of concrete spraying, the rebars are slightly covered in concrete, hence have to be cleaned by pressurised air. This is a result of the joining points being crucial for the overall force transition between the discrete elements. An automated cleaning of the joint can be integrated as a function in an end-effector for rebar joining. For this, a ring-shaped air nozzle mounted to the end-effector is being positioned on top of the concrete covered rebar. Then, the pressurised air will clean the rebar from all sides.

Additionally, the orientation and handling of rebars is highly relevant for achieving the optimal performance. Via automated handling the rebars, the precision of the process could be ensured. Using a robotic application, a specific end effector could hold and join the reinforcement elements for high precision. Alternatively, when employing human machine cooperation, an augmented reality (AR) application could be utilised to help with the placement of the rebars in the correct position for the welding process.

The heat production of the welding process has to be monitored and a cooling mechanism has to be established. Elevated temperatures in the rebar within the concrete accelerate water evaporation, consequently introducing alterations in the concrete's structural integrity and the bonding quality of the rebar. Cooling mechanisms such as forced convection cooling with pressurised air or conductive cooling by gripping the joint utilising a highly heat conductive material. Furthermore, a detailed investigation on the exact temperatures at the welding joint. Additionally, cold joining processes have to be investigated. Moreover, the elevated rebar temperature as potential influence on the reinforcement bond quality has to be examined as a crucial parameter of overall mechanical performance.

The proposed segmentation strategy focusses on minimising production time by reducing the preparation steps of the rebar. Furthermore, the algorithmic approach allows for the adjustment of thresholds to control the approximation of the force-flow trajectory. A tight approximation can significantly increase the flexural strength of the reinforcement layout as presented by Dörrie et. al. [27] but also potentially increasing the number of joints. Alternatively, a prioritisation focused on the mechanical properties can be applied by reducing the number of joints, minimising heat introduction and potential points of failure. Furthermore, within mechanical properties, the reinforcement concrete cover and surface finishing can serve as determining parameter. Particularly slender components can be manufactured due to the absence of formwork and the requirement for mechanical vibration. By incorporating a surface treatment or supplementary cover layer, an adequate concrete cover can be provided and the durability enhanced.

Comparing both reinforcement processes, the BRJ process allows for a close approximation of the force-flow and minimises stress peaks in the reinforcement layout. However due to the complex bending of the segments, the duration of the rebar preparation is increased. The SRJ process potentially achieves less structural performance due to coarser approximation of the force-flow trajectory and more stress peaks. The preparation time is decreased due to the use of straight elements. Therefore, the segmentation strategy offers the combination of the different techniques by utilising each process strength in the approximation of individual force-flow trajectories.

5. Conclusion and outlook

The presented research highlighted three concepts for reinforcing complex concrete elements using discrete rebar segments. The proposed methods include: (A) integration of straight rebars, (B) joining of short straight rebars, and (C) joining of pre-bent rebar elements. Each concept enables varying degrees of alignment with the structural force-flow, thereby improving mechanical performance and enabling material savings.

Concept A is suitable for linear geometries and supports high-speed printing by few printing interruptions with minimal complexity.

Concept B offers an improved alignment with force trajectories through prefabricated, angled segments, facilitating a more structured and repeatable printing sequence.

Concept C allows for the most accurate depiction of the force-flow and delivers the highest performance potential, although at the cost of reduced printing speed due to a comparably complex integration process.

Further investigations should address the impact of the joining process on the printed concrete. The thermal and mechanical loads of the joining process can influence the reinforcement bond and therefore impact the structural integrity. The investigation of different joining processes and manipulation strategies can show possibilities for reducing this impact. For future implementation, automation is essential. Robotic placement and joining of rebar elements can ensure the necessary precision and efficiency. Additionally, human-machine collaboration concepts, supported by AR, may streamline reinforcement placement and enable real-time adjustments. These approaches pave the way for fabricating highly complex, performance-optimised concrete structures through additive manufacturing.

Data availability statement

Data supporting the results of this article are available upon request.

Author contributions

Conceptualisation: RD, MM, MD, KD, HK; Data curation: RD, MM; Formal analysis: RD, MM, MD; Funding acquisition: RD, MD, KD, HK; Investigation: RD, MM, MD; Methodology: RD, MM, MD; Project administration: KD, HK; Resources: KD, HK; Software: RD, MM, MD; Supervision: KD, HK; Validation: RD, MM, MD; Visualisation: RD, MM, MD; Writing – original draft: RD, MM, MD; Writing – review & editing: RD, MM, MD, KD, HK

All authors have read and agreed to the published version of the manuscript.

Robin Dörrie and Manuel Megnet contributed equally

Competing interests

The authors declare that they have no competing interests.

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