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Article

Combined Additive Manufacturing Techniques for Adaptive Coastline Protection Structures

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Abstract: Traditional reinforcement cages are manufactured in a handicraft manner and do not use the full potential of the material, nor can they map from optimised geometries. The shown research is focused on robotically-manufactured, structurally-optimised reinforcement structures which are prefabricated and can be encased by concrete through SC3DP in a combined process. Based on the reinforcement concept of "reinforcement supports concrete," the prefabricated cages support the concrete during application in a combined AM process. To demonstrate the huge potential of combined AM processes based on the SC3DP and WAAM techniques (for example, the manufacturing of individualized CPS), the so-called FLOWall is presented here. First, the form-finding process for the FLOWall concept based on fluid dynamic simulation is explained. For this, a three-step strategy is presented, which consists of (i) the 3D modelling of the element, (ii) the force-flow analysis, and (iii) the structural validation in a computational fluid dynamics software. From the finalized design, the printing phase is divided into two steps, one for the WAAM reinforcement and one for the SC3DP wall. The final result provides a good example of efficient integration of two different printing techniques to create a new generation of freeform coastline protection structures.

Keywords: coastline protection structures; robotic fabrication; shotcrete 3D printing (SC3DP); additive manufacturing in construction (AMC); wire-and-arc additive manufacturing (WAAM)

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1. Introduction

In traditional onsite fabrication, reinforcement cages and concrete walls are produced in a handicraft and not a resource-efficient manner. When fabricating a concrete element, first a formwork must be installed, and reinforcement elements have to be integrated. The reinforced formwork is then filled with concrete to encase the reinforcement and hold the concrete for the duration of the curing phase. However, this traditional approach comes with certain limitations, such as the restriction of geometrical freedom due to the formwork and the lack of material efficiency of the reinforcement.

Current research into 3D concrete printing (3DCP) aspires to solve these limitations. The 3D extrusion of concrete, contour crafting, particle bed printing, and the novel technique of shotcrete 3D printing (SC3DP) enable the user to produce geometrically complex structures without a formwork [1–5]. Nonetheless, most of these structures do not exploit the full potential of 3DCP. Therefore, the integration of reinforcement has to be considered, and it has to be distinguished from masonry-like 3D printed and reinforced concrete-type structures. Ongoing research examines the integration of reinforcement into 3D printed concrete elements [6–10]. Various integration methods and materials are used to reinforce the printed components. However, they are mostly limited to one type of construction element.

The production of metallic structural elements can be performed by employing different metal additive manufacturing (AM) processes, which are classified as powder bed fusion (PBF), directed energy deposition (DED), and sheet lamination. Within the category of DED processes, wire-and-arc additive manufacturing (WAAM) is the most suitable for realizing large-scale metal parts for structural engineering purposes due to the setup flexibility, ideally with no geometrical constraints related to the dimension and shape of the printed parts [11,12]. WAAM is defined as the combination of using an electric arc as a heat source to melt the wire feedstock and deposit a droplet, layer-by-layer. WAAM-produced elements require additional considerations when dealing with their mechanical characterization. First, detailed geometrical characterization of the irregularities and surface roughness of the printing strategy is needed to assess the possible detrimental influence on the mechanical response of the as-built elements. Then, it is necessary to check for certain degrees of material anisotropy present from the directionality of the printing process, which alters the mechanical response based on the relative printing direction. In particular, stainless-steel members produced with WAAM have revealed marked orthotropic behavior induced by the orientation of the microstructure [13]. Additionally, the process parameters affect the printing quality and, consequently, the mechanical response of the printed elements [14].

In this study, a combined AM process is presented to realize a new generation of structurally-optimized elements; shotcrete 3D printing (SC3DP) and wire-and-arc additive manufacturing (WAAM) are used in combination to fabricate highly efficient reinforced 3D printed concrete elements. The absence of a formwork allows for exploring new efficient geometries adapted to the environment where the reinforced concrete structure will be located.

Based on the principle of tensile, stress-compliant reinforcement alignment, the reinforcement structure can serve as the basis for the concrete application. Indeed, the reinforcement itself can be shaped by orienting itself to the force flow. This concept is called "reinforcement supports concrete" (see Figure 1) [4].

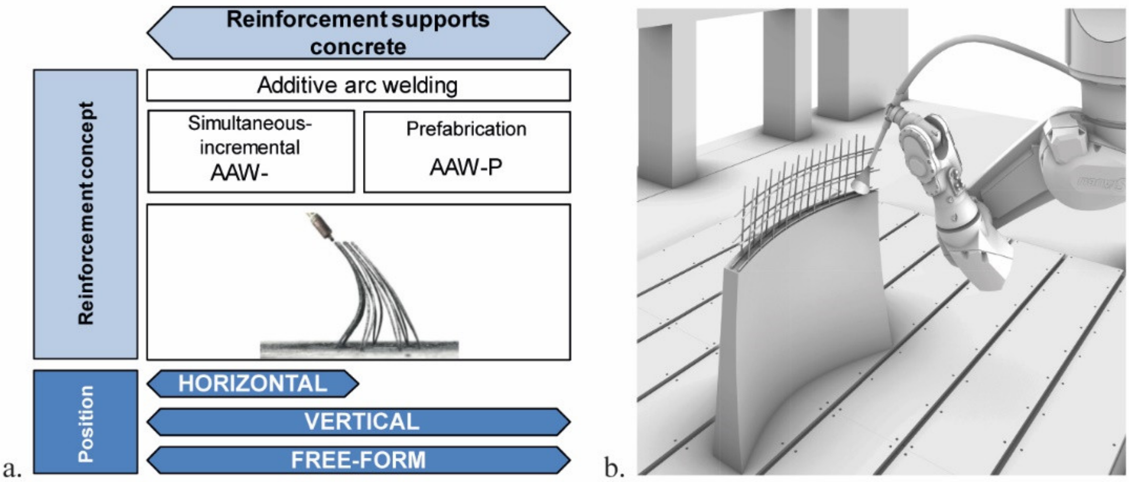


Figure 1. (**a**) Concept of reinforcement supports concrete (**b**) Robotically and automated encasing of prefabricated reinforcement structure by SC3DP.

The presented work is focused on a specific application of the combined AM process adopted to realize urban coastline protection structures (CPS). The individualized and eco-integrated coastal protection structures are a sustainable, economical, and adaptive way to repopulate dead coast sections and bring in marine life, thus bringing healthier bodies of water into the urban landscape and strengthening the bond between urban life and nature. Section 2 reports a brief overview of CPS, from the background to the concept of adaptive CPS as presented in this manuscript. Section 3 describes the two AM technologies adopted for the present case study (i.e., shotcrete 3D printing and wire-and-arc additive manufacturing). The computational design approach used for the adaptive CPS is reported in Section 4 while the first experimental application is presented in Section 5. Finally, some conclusions and future perspectives are drawn in the end.

2. Coastline Protection Structures (CPS)

2.1. Background

Coastal cities are home to more than half of the world's population and are the focal point of business activities. However, in the last few decades, climate change has induced sea level rise, and, consequently, the land has been reclaimed by seas and estuaries. This is in the opposite direction of human activities in coastal cities, which are expanding to gain living space in response to the migration towards the cities. As a consequence, the need for coastline protection structures (CPS) is increasing [15].

Traditionally, the design of coastline protection structures has been based on the resistance to the impacts of nature and does not take into account the negative impact on ecosystems and marine environments. Traditional coastline protection structures are mostly based on prefabricated, mass-produced concrete elements, sheet piles, or rubble-mount structures. These CPS solutions are not aligned to the adaptation concept, which is to re-establish the original ecosystem at the end of the construction. Recently, the novel concept of nature-based solutions introduced a philosophy that designs 'with' rather than 'against' nature [16,17]. In many places worldwide, however, coastal zones diminish towards mere coastline (i.e., 'coastal squeeze'), exacerbating the challenge to reconcile the marine ecosystem and coastal protection. City planners and coastal engineers require scientific knowledge to holistically govern the design-production-construction chain and adopt biodiversity-enhancing strategies, digital fabrication advantages, and new coastal protection strategies that contribute to new life in formerly dead CPS [18].

The presented application is a novelty in the urban coastline protection environment due to the adoption of advanced digital technologies for individualized and eco-integrated designs of CPS. This will necessitate (1) a highly individualized design and fabrication of construction elements, (2) predictive capabilities towards the ecological response to artificial structures, and (3) an improved understanding of the interaction of water levels and wave impacts on CPS.

2.2. Adaptive CPS

The adaptive CPS can be manufactured with the novel combined additive manufacturing process, consisting of shotcrete 3D printing (SC3DP) and wire-and-arc additive manufacturing (WAAM). The SC3DP process enables the production of free-form concrete structures without formwork while the reinforcement is provided using the WAAM process, which builds up a 3D steel structure. The coastline protection is integrated into the marine environment: adapting its shape to its natural surroundings, rearranging locations for marine plants, and setting up a new habitat that defends the original ecosystem (Figure 2).

Figure 2. Rendering showing the adaptive urban coastline protection structure.

A prototypical section of an adaptive CPS was produced using two additive manufacturing techniques in a combined process. First, the computational design is explained following the two AM processes; then, the first experimental application is discussed.

3. AM Systems for New Generation of Urban Coastline Protection

3.1. Wire-and-Arc Additive Manufacturing (WAAM)

In this work, the "dot-by-dot" printing technique is applied to realize a force flow-oriented WAAM steel grid reinforcement for a SC3DP wall.

The "dot-by-dot" printing process consists of a droplet of steel derived from the steel wire welding, its solidification, and the subsequent deposition of a new droplet on top of the previous one by repeating this iteration until the end of the work [12,13,19,20]. Each iteration includes seven steps. (i) The robotic arm arrives at the droplet location; (ii) the gas pre-flow turns on; (iii) the arc process starts; (iv) the robotic arm moves upward in the building direction with a settled welding speed and seam height; (v) the arc process ends; (vi) the gas post-flow turns on, protecting the welded droplet as it starts its solidification; and (vii) the robotic arm moves towards the next droplet, ensuring the cooling time of the welded droplet. The presented steps are repeated to manufacture subsequent layers up to the target height required for the outcome.

The cooling time is associated with the droplet's mass and the distance between the droplet and the cooling plate. They change layer-by-layer; therefore, the cooling time increases as it proceeds upward, determined by a change in heat transfer speed over time. The fabrication of more droplets on the same layer guarantees the cooling time of each droplet, speeding up the manufacturing process by removing idle time.

3.2. Shotcrete 3D Printing (SC3DP)

The application strategy of SC3DP involves an adjustable printing angle and distance to the sprayed surface, which facilitates the integration of certain functions, installations, components, and complex reinforcement structures [21]. As a result of the acceleration and radial distribution of the concrete, a proper embedment and bonding between the reinforcement structure and concrete are achieved. Moreover, in contrast to 3D extruded elements without reinforcement that structurally work mostly as masonry (low interlayer strength), SC3DP can attain almost monolithic structures such as casted concrete elements. This way, traditional construction elements, as well as complex geometries, can be produced. However, the surface quality is still open to research. While 3D extrusion offers a clean layer-by-layer structure on the outside, SC3DP appears to have a rough surface which can be used to apply a second vertical material layer or can be smoothed with a postprocessing application. Furthermore, compared to the extrusion process, SC3DP has the advantage of an easier integration of reinforcement or functions due to the nozzle distance and the material application with high kinetic energy.

Therefore, SC3DP offers a wide range of reinforcement integration possibilities [4]. “Reinforcement supports concrete” is the most promising concept to adapt for SC3DP since different challenges occur with simultaneous integration of reinforcement.

Instead of a formwork, the reinforcement structure is placed to guide the concrete and hold it in place [22]. Possible structures include traditional rebar cages but also WAAM structures or other materials that can be assembled as a contiguous structure. Furthermore, the structures could be assembled during the process step-by-step before the applied concrete covers the previously placed reinforcement. For example, the reinforcement could be divided into 20 cm high segments which are installed subsequently.

Nevertheless, a prefabricated structure provides a general support to the printed concrete and allows a quicker build rate than without support. The strongly-profiled surface of the WAAM rebar shows good bonding, which increases the cohesion between concrete and reinforcement during printing, preventing the material from sagging or collapsing [23]. Preliminary work showed this effect with traditional reinforcement structures as well. Furthermore, the close-knit, force-flow-oriented structure amplifies this effect.

4. Computational Design Approach for Adaptive CPS

The design process for the presented concrete element follows a three-step strategy that consists of the 3D modelling of the construction element, force-flow analysis, and validation of the structure in computational fluid dynamics software. The approach is heuristic, as the initial input geometry is designed first and later adaptively optimised across different parameters.

Initially, a double-curved, free-formed wall is designed and analysed. This wall represents a segment that is part of a CPS. To create the virtual element, the 3D modelling software Rhinoceros was used (see Figure 3a).

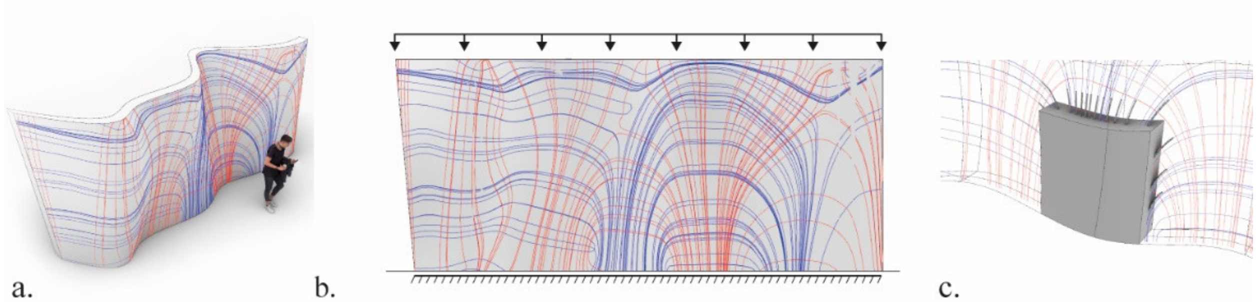
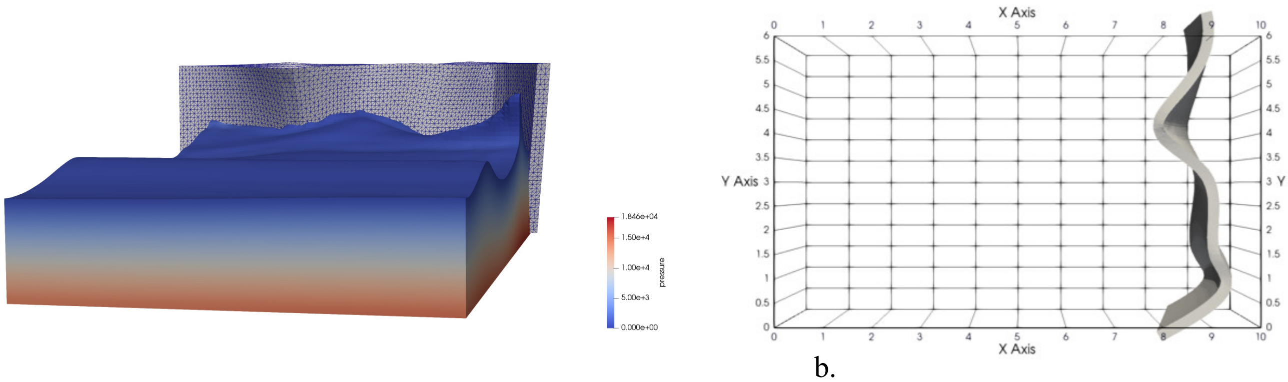


Figure 3. (**a**) prototypical free form wall as part of a building (**b**) assigned loads and supports to curved wall and visualised force-flow. Encased WAAM structure in stress visualisation (**c**) selected section to manufacture with WAAM.

In the next step, the proposed CPS element is analysed according to the assigned load cases. The complexity of the wall element generates out-of-plane stress even for the self-weight load configuration. The stress state under loading conditions is evaluated using the software Karamba [24]. This finite element (FE) program is embedded into the parametric workflow of Grasshopper; it enables the visualisation of the stress trajectories inside the construction element. In this case, a line load along the length of the wall and a clamped support over the full length of the wall were assigned. Figure 3b shows the visualised stress lines that occur due to the assigned load. The tension lines are marked blue, and the pressure lines are marked red.

The performative advantage of the double-curved wall is verified using a computational fluid dynamics simulator, of which the integration in the modelling process contributes to more precise load definition for subsequent reinforcement optimisation. A number of open-source codes, as well as commercial computational fluid dynamics (CFD) software, is available for analysis of fluid–structure interaction. The primary requirement for using one instead of the other is the availability of the option of importing a digital 3D object (an .stl or other type of file) into the simulated environment, which is usually a numerical water tank. The imported three-dimensional body is defined either as rigid or deformable depending on the simulation type and parameter availability, which directly affects both the input and the output data. REEF3D is such a type of computational fluid dynamics software developed at NTNU [25]. The geometrical data of the FLOWall is imported into REEF3D and placed at the end of the numerical water tank, simulating a seawall whose function is reflecting oncoming waves (see Figure 4). The body is defined as a rigid, nonporous media, and simulations of ideal reflection and waves are generated at X coordinate 0 (zero) using the Dirichlet boundary definition with absorption.



a. b.

Figure 4. (**a**) Mesh resolution of the wall used in CFD [17], (**b**) Wall's .stl file imported into REEF3D [25] with designated force box.

The force box/cylinder in Figure 5 generates the output of the resulting force in each direction (i.e., water pressure integrated over the respective perpendicular area).

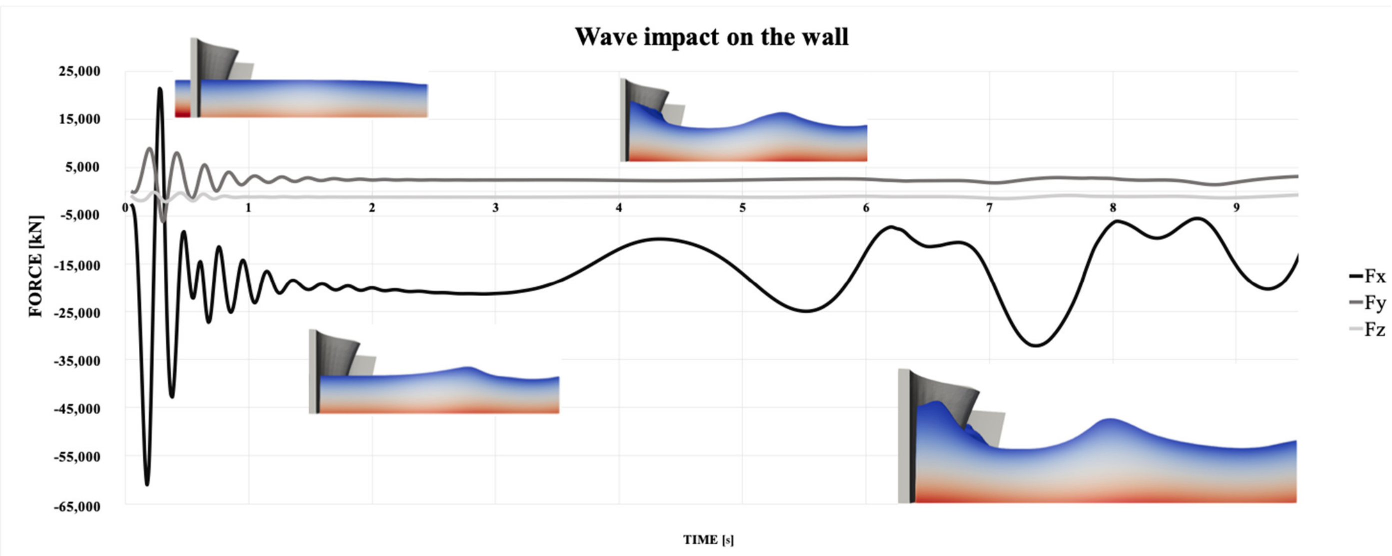


Figure 5. Scenes/screenshots from 10s simulation of water wave reflection by seawall (FLOWall), Load data extraction from CFD model; initial active wave generation is ignored, stabilized data is considered for further design.

Positive values of the force box output (Fx, Fy) in the moments of wave generation [0–1s] can be explained as passive action on the wall before the water wave moves through the space of the numerical tank (see Figure 5, upper left corner) and can be ignored. In general, CFD results enable almost precise load definition for the purpose of structural optimization and consequent material reduction. Over a 10s wave simulation, several waves are reflected. The wave that results in impact with the highest load is identified, and its data is extracted. At that instance of time (i.e., simulation time), load variations along the height of the wall are captured, and newly-defined load cases are implemented back in the Karamba 3D simulation for the adaptation of the stress lines. The reinforcement is adapted consequently.

According to the CFD analysis, a feedback loop was created which could then influence the design of the CPS and improve the overall structural shape as well as the water dynamics of the CPS and the ecosystem in the area. The CPS could be re-evaluated and adapted to the results.

For further investigation of the concept, a section from the wall was chosen for production. As seen in the analysis (see Figure 3c), the bottom center of the wall is under high tensional stress. This area is now isolated and will be reprocessed for each manufacturing technique individually.

5. First Experimental Application

As a first demonstration, a portion of a CPS structure was manufactured by making use of the combination of AM processes (i.e., SC3DP and WAAM).

The reinforcement was produced by adopting WAAM technology among all possible metal AM methods. The welding setup was composed by a Universal Robot (UR16e) as a motion system and Fronius TPS 600i PULSE as a power source, equipped with cold metal transfer (CMT) to control wire deposition with reduced heat that is transferred to the layers under deposition, ensuring cooling [14]. As a consequence, the outcome was inherently influenced by the welding process parameters adopted during the printing process. In this study, the focus was pointed toward the following parameters: wire diameter, wire feed speed (Wfs), current (I), voltage (U), arc-length correction, inching value, start, slope and end current, and gas pre- and post-flow. The reported WAAM process parameters refer to input and output parameters (Table 1), welding, and geometric and motion parameters (Table 2).

The shielding gas was a mixture of argon (Ar) and 15–20% carbon dioxide (CO_2), also known as M21, and was applied with a constant flow of 15 l/min. The target layer thickness is defined as 1.0 mm, whereas the corresponding real counterpart is influenced by the input parameters. The printing process of a WAAM structure is shown in Figure 6.

Table 1. WAAM process parameters.

Input Process Parameters			**Output Process Parameters**	
Current	**Voltage**	**Wfs**	**Welding Time**	**Robot Speed**
I [A]	U [V]	[m/min]	[s]	[mm/s]
108	13.7	3	1.2	1000–1200

Table 2. Constant welding, motion and geometric parameters.

Wire Diameter	Layer Height	Seam Height	Welding Speed	Arc-Length Correction	Inching Value	Starting Current	Start Current Time	Slope 1 and 2	End Current	Gas Pre Flow	Gas Post Flow
[mm]	[mm]	[mm]	[mm/s]		[m/min]	[%]	[s]	[s]	[%]	[s]	[s]
1.2	1.0	1.0	1.0	−2.0	3.0	135.0	0.2	1.0	50.0	0.5	2.0

Figure 6. Printing process of a WAAM lattice structure.

To encase the WAAM structure and build up a concrete structure, the novel technique of shotcrete 3D printing was used. This system is part of the Digital Building Fabrication Laboratory (DBFL) at the ITE at TU Braunschweig. The setup consists of a Stäubli TX 200 robot with 6 degrees of freedom which is attached to a 3-axis gantry portal that was provided by OMAG SpA. The end effector was attached to the robot and was designed to accelerate the fresh concrete through pressurized air and blend it with accelerating fluids to speed up the hardening process of the concrete. The concrete production and conveying line, which distributes the material towards the end effector, consisted of a WM-Jetmix 125 pug mill mixer by Werner Mader GmbH and a WM-Variojet FU Pump. The material used for spraying all of the components was a conventionally available sprayable mortar produced by MC Bauchemie (MC Bauchemie-Müller GmbH & Co. KG, Bottrop, Germany).

This setup and certain parameters were used to encase the WAAM structure with concrete (Table 3).

Table 3. SC3DP process parameters.

Printing Angle	Nozzle Distance	Robot Speed	Concrete Flow	Air Flow
[°]	[mm]	[mm/min]	[m³/h]	[m³/h]
85	200	4500	0.4	40

Additionally, the path planning had to be set up for the robotic application of the concrete. The complex printing paths were also programmed utilizing the interface of Grasshopper in combination with “Robots,” a plugin developed by the Bartlett School of

Architecture. Hence, the designed structure and the robotic fabrication were visualised in one interface.

Since the prefabricated reinforcement structure was already in place for fabrication, a non-perpendicular concrete spraying was applied. First, the path planning was horizontally planned according to the complex geometry of the wall as a basis. Second, the robot path was correspondingly tilted to the curvature of the wall, making the nozzle perpendicular to the surfaces' normal vectors in all points of the robotic path and spraying the concrete compliant to the surface layer-by-layer. This way, the precision of the application could be increased since overhangs between layers were compromised and the surface structure followed the designed object (see Figure 7).

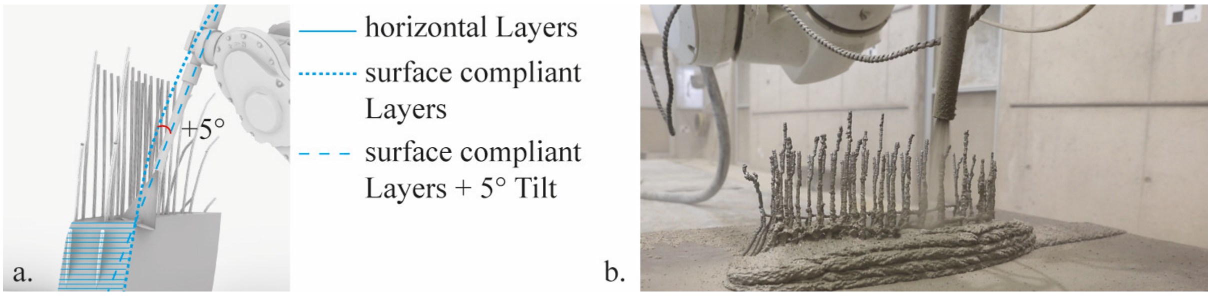


Figure 7. Different steps in path planning and printing process: (**a**) graphical representation of the printing relative inclination, (**b**) frame of the experimental printing phase.

Third, the application direction was tilted an additional five degrees to avoid a collision with the prefabricated structure. The initial nozzle distance combined with a five-degree tilt generated a safe distance from the structure while not compromising the strand geometry of the SC3DP process.

This path planning process was completed for the front and the back of the reinforcement structure. To reach the initially set wall thickness of 240 mm, a two-strand application was chosen. Each time, a 125 mm strand was applied with a slight overlap in the middle to ensure a monolithic composition and effective bonding of the reinforcement structure. Finally, the convex face of the structure was postprocessed to attain a precise surface quality. Due to the scale of the produced specimen, the postprocessing was done manually.

Figure 8 shows the final result. The force-flow-oriented reinforcement structure was encased by concrete and could serve as a prefabricated construction element.

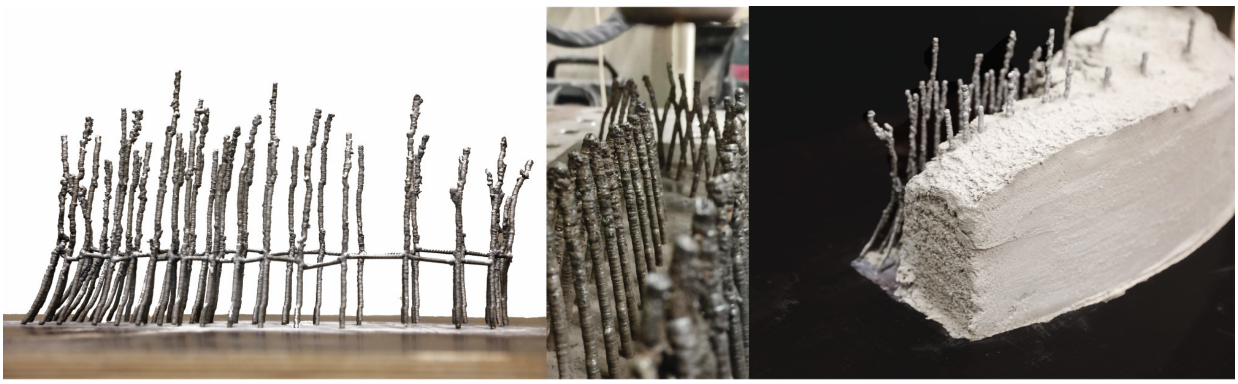


Figure 8. Final SC3DP specimen with integrated force flow compliant WAAM reinforcement structure.

Despite the high degree of freedom for 3D force-flow-oriented reinforcement structures, the simultaneous or prefabrication of WAAM structures is not yet feasible due to its low material application rate and required cooling rate [26]. An increase in process speed or a combination with short rebar integration is necessary for fast manufacturing and coordination of the processes towards each other.

6. Conclusion and Outlook

This study focuses on the combined manufacturing of adaptive and ecological CPS with SC3DP and WAAM as a reinforcement structure. The following conclusions can be drawn from this study.

The combination of the SC3DP process with WAAM to produce prefabricated reinforcement structures brings forth a fully-automated manufacturing process, which can be used for several applications using reinforced concrete. The high degree of geometrical freedom in both processes offers new possibilities for the building industry as well as for infrastructure projects like the prototypically manufactured CPS. Formwork is no longer necessary, and it is possible to prefabricate all elements or even produce them *in situ* with mobile robots, although with possible limitations such as non-laboratory conditions, the influence of the saltwater environment on the robots, and materials.

Furthermore, it was shown that the concept of prefabricated reinforcement structures is a viable concept to reinforce 3D printed structures by SC3DP. Both the SC3DP and the concept allow the assimilation of many integrated variations and materials. The prefabricated structure acts as a strong support to increase the build rate and stability of the print.

Finally, the experimental result was discussed. The feasibility of the welding process has to be improved based on the application and cooling rate of the WAAM process. However, the WAAM rebars offer increased strength and bonding compared to traditional rebars and can additionally be force-flow-oriented for even higher utilization, hence higher efficiency.

Future research will focus on shape-optimized geometries and the increase of both efficiency and sustainability of the CPS element by reducing the amount of concrete used compared to the traditional casting process. Furthermore, the presented three-step strategy will then be followed up with final adjustments of the shape based on the recent advances in the domain of urban marine ecology in the form of final texture, crevices, pits, or even material readjustment [27,28]. This way, the combination of structural optimization and ecological optimization results in ecofriendly CPS to revive and re-naturalize coastlines.

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