Structural Cellulose

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Abstract. The paper presents a novel design to fabrication strategy that deploys inherent structural properties of bio-composites based on a cellulose-casein mixture. The design and fabrication pipeline involves multiple iterations of robotic spraying including feedback operations based on iterative 3D scanning. This allows to adjust the geometry, to regulate material distribution, and to modify the path generation regarding the spraying with the industrial robot. It also enables vision-based monitoring or repair measurements and allows to observe failure or cracks in relation to the hidden material structure. Several studies are discussed in detail that deployed the "adaptive" robotic spraying method of cellulose-based mixtures on two distinct textile substructures: a winded rope structure and fabric tubes. The mechanical properties of the sprayed cellulose-casein composite material are predicted, based on multiscale micromechanical modelling.

Keywords: digital fabrication, adaptive robotic spraying, volumetric design, structural cellulose, cellulose-casein mixture, feedback between design and fabrication

1 Introduction

The overall aim of the research is to develop a sustainable design and robotic fabrication method that exploits the structural properties of cellulose-based composites. The additive method is based on spraying cellulose layers onto textile substructures and offers a high degree of customizability in terms of internal structure, material distribution and the aesthetic, geometric, and structural properties of the results. Each sprayed layer is scanned and recorded as a point cloud, resulting in a complex digital model of superimposed production steps.

To establish such a complex design and manufacturing process, which includes feedback loops between design intentions, material behaviour and fabrication constraints, an "adaptive" robotic spraying strategy is used. As the cellulose mixture is applied in several iterations to dry and cure in between, a re-adjustment of the following robotic spraying step becomes possible. For example, the designer can create spontaneous changes to textures and surfaces during production by changing the angle of the end effector (see Fig. 1).

A long-term goal of the research is to make such manufacturing process adaptations accessible in real-time to the designer through an embedded simulation of material behaviour.

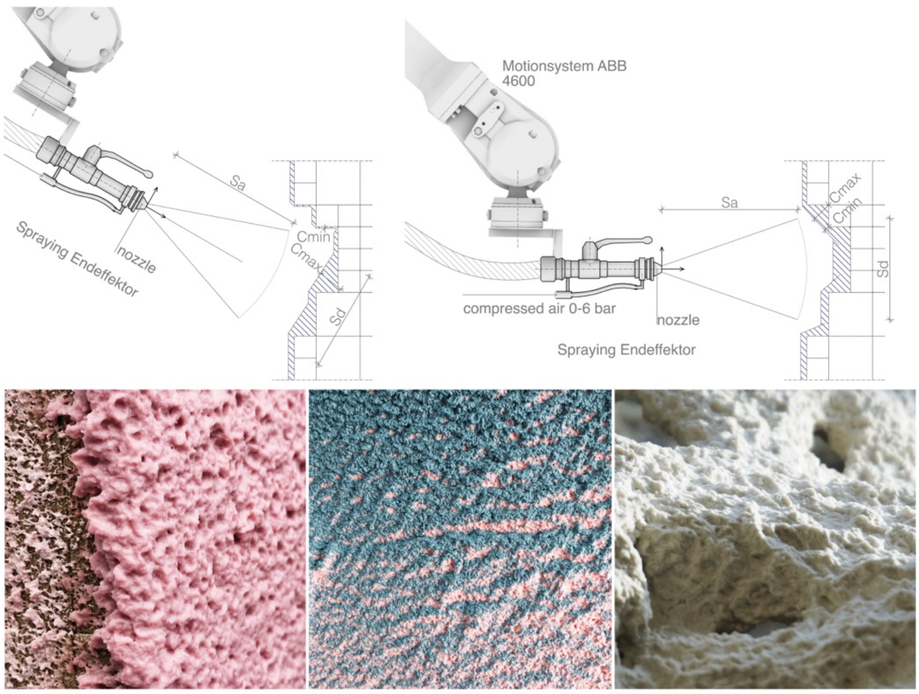

Fig. 1. Adaptive details achieved through changing the spraying direction (top) and samples with different colouring and textures (bottom)

2 Background

Robotic spraying of materials such as clay (Gosch et al., 2022), plaster (Mitterberger et al., 2022) or fibre cement (Jipa et al., 2023) is often used in a surface approach, however, this paper suggests a “volumetric” strategy (Wimmer et al., 2022) that a) creates heterogeneous layers and material distribution and b) deploys spatially differentiated textile substructures (Schinegger et al., 2020; Gil Pérez et al., 2022).

Robotic spraying was introduced in 1998 as a method for creating prefabricated panels (Penin et al., 1998). A CAD system was used to create a 3D drawing of the building as input, from which the optimal facade subdivision was derived. The panels were made of Glass Reinforced Cement (GRC) and were sprayed onto prefabricated formwork. This technology is similar to shotcrete 3D printing (Kloft et al., 2019). Fully automated path planning systems for robotically spraying concrete have been used in construction purposes like tunnel construction (Girmscheid and Moser, 2001). Furthermore, the aesthetic and design potential of robotic spraying has been explored in architectural applications, i.e. like surface treatment of reinforced concrete elements (Taha et al., 2019). The automatization of robotic spraying processes was supplemented with monitoring and measuring strategies, i.e. based on a depth-camera-based rebar detection and digital reconstruction for robotic concrete spraying (Frangez et al., 2021).

In architecture, bio-based and biodegradable materials have been widely used in robotic 3D printing prototypes (Thomsen and Tamke, 2022). Processes were implemented to 3D print free-form objects made from cellulose with different binders, which had a significant impact on the further development of the associated material. It is worth noting that these materials have not yet been widely adopted in other digital production processes. The pulp pavilion (Ball-Nogues, 2015) was a structure made of composite materials, including reclaimed paper, that was hand-sprayed for the Coachella Valley Music Festival.

3 Methods

3.1 Design to fabrication workflow

The cellulose mix needs to be applied in thin layers of 2 to 6mm since it stiffens through the evaporation of water. Consequently, the design and fabrication pipeline involves multiple iterations including feedback operations. A 3d scan and its corresponding point cloud serves as the backbone of this feedback operation, allowing the designer to adjust the geometry, to regulate material distribution, and to modify the path generation regarding the spraying operation with the industrial robot.

After the fabrication step, point clouds are used to predict the design of the geometry. Generally, the point cloud data also needs to document per point normals to process the presented pipeline.

The design loop consists of the following steps:

1. The design input is given through a point cloud of the substructure. In the first iteration this could be established by a digital design model converted to a point cloud (e.g. through sampling) or simply using a first 3D scan.
2. The material distribution can be regulated based on a desired material thickness, so each point would provide associated data representing the envisioned volume. This can be controlled by a reference model, structural analysis or direct interaction.
3. The generation of the robot paths is based on the point cloud and its skeleton graph. The end effector alignment is based on this central graph and the corresponding closest points and their normal. The base alignment is given by limited circular movements along this graph, the limitation is given by the reach of the robotic arm or other spatial constraints. To achieve the composite material distribution described in (2.) the speed of the robot can be adjusted.
4. This step includes the simulation of the robot path connected to a simplified particle simulation that also checks the material distribution. In the case of insufficient results step (3.) can be repeated to generate a better alignment.
5. Eventually the robotically assisted spraying is carried out and the wet cellulose mix is applied onto the substructure.

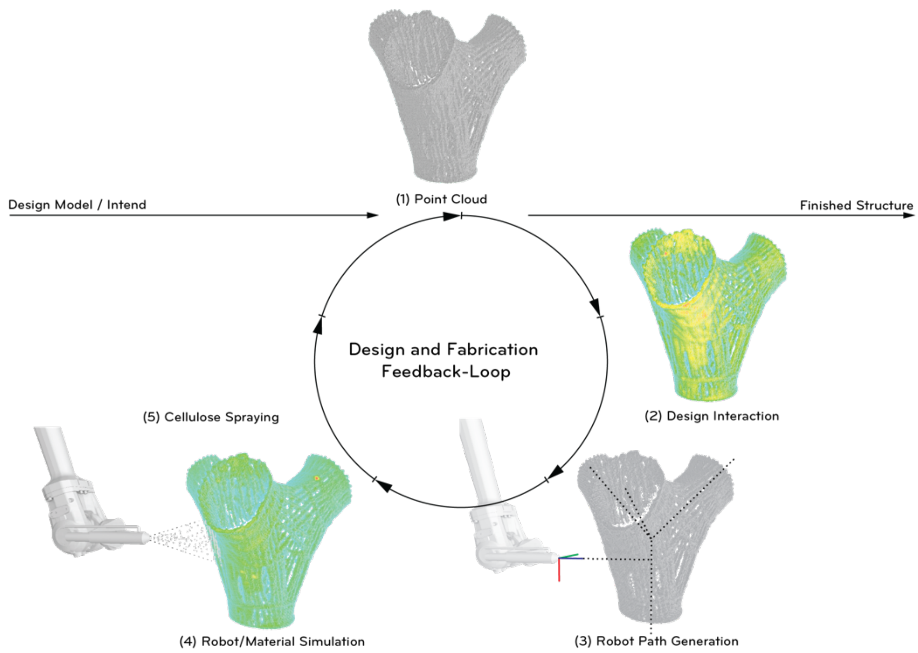

Fig. 2. Design and Fabrication Feedback-Loop

A further advantage of the point cloud approach is that the information of the sprayed layers is stored in the model through iterative scanning of the results. This allows further vision-based monitoring or repair measurements and allows to observe failure or cracks in relation to the hidden material structure (Tamke et al., 2023).

3.2 Robotic Spraying process

The material is first mixed to a homogeneous mass in a compulsory mixer, where the underlying viscosity is also adjusted via the water content. In the feed pump, the material is then conveyed under pressure and speed-controlled via a hose to the spraying end effector. An ABB 4600 6-axis robot serves as the motion system. The material arrives at the end effector under a controlled pressure of between 4 and 15 bar and is then atomized by a nozzle under air pressure, controlled between 0 and 6 bar. The atomized material emerging in a cone has a distribution angle of approximately 70 degrees. On an experimental basis the distance between the end effector and the substructure should be in the range of 40 to 80 cm (see Fig. 3).

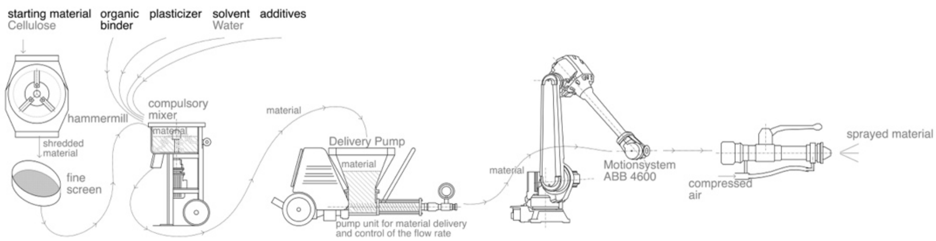

Fig. 3. Robotic spraying process diagram

3.3 Bio-composite development

As high material consumption was to be expected for the additive spraying process described above, a proxy material was developed to keep material costs low. A biological and biodegradable material based on cellulose was chosen, therefore a long-fibre cellulose with an average fibre length of 0.5 mm was selected. As with the filling material, a renewable, biodegradable material, casein, was used as the binding agent (Melnychuk et al., 2021). Casein is precipitated lactic acid, a protein component of milk. The powder casein swells in water and then solubilizes with marsh lime.

The material was mixed in coordinated weight proportions in a compulsory mixer to form a homogeneous mass and brought to a machine-compatible viscosity range using water as a solvent. The prototype mixture has a high-water content to enable pumpability with the delivery pump. This prioritizes processability over mechanical properties. The prototypes in the research used a 13% (by mass) long-fibre cellulose mixture. Purified cellulose from the paper industry was utilised as the source material, as recycled cellulose from newsprint is often contaminated with printing ink residues and a high proportion of mould spores. The solvent used was 74% water, with 4% marsh lime, 1% sodium, and 8% casein employed as a binder.

Due to the use of water as a solvent, the material dries out as the water evaporates. Longer drying times are required due to the high-water content in the uncured mixture. The curing process typically takes up to 24 hours when applying layers of several millimetres. The drying room's climate is crucial, with temperature and humidity being the most significant factors. The material behaviour during the drying process is causing warping, crack formation and shrinkage, which leads to a decreased structural capacity. With decreasing drying time, the occurrence of unwanted effects and deformation increases. Thus, future research should focus on reducing the water content and the adaption of the spraying hardware. A sequential build-up of the pipe structure allows for faster curing and drying and enables an adaptive cross-section for gradual structural performance (see Fig. 4).

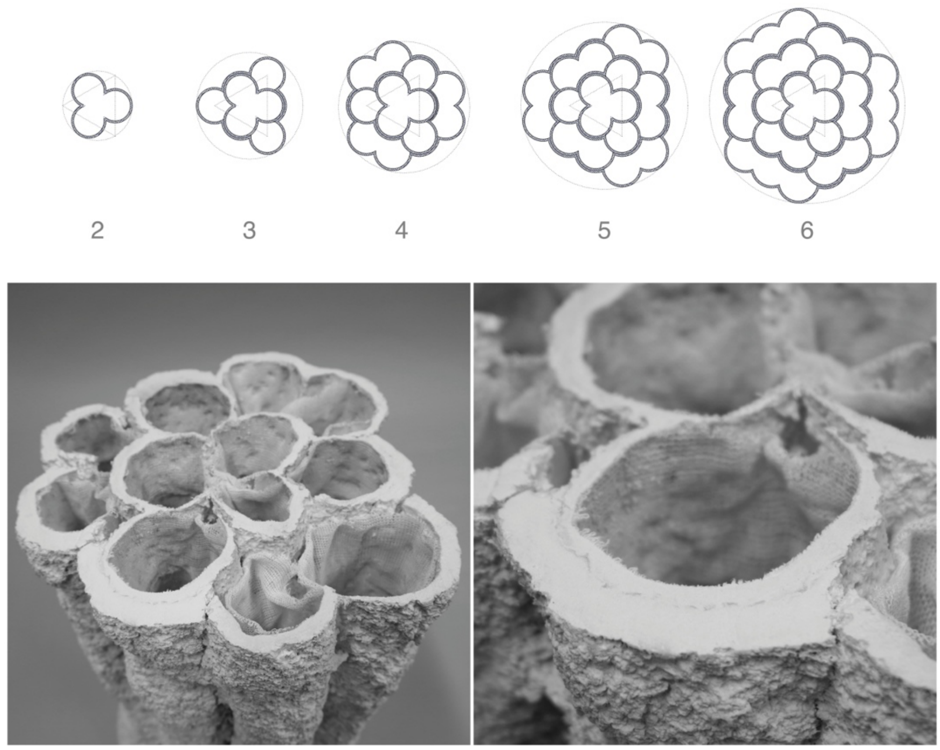

Fig. 4. Step-by-step production by adding layers (top) and a sectioned prototype (bottom)

3.4 Structural Material Properties

The evaluation of the structural capacities of the specific bio-composite is a crucial aspect to establish a design workflow that takes realistic material properties into account. The mechanical properties of the sprayed cellulose-casein composite material are predicted based on multiscale micromechanical modelling (Königsberger et al., 2023, 2024). The complex heterogeneous microstructure is thus simplified. Typical cellulosic pulp fibres are considered (68% cellulose with crystallinity index of 63%, 26% hemicellulose, and 6% lignin; microfibril angle of 15°), with spheroidal shape (500 microns long, 20 microns in diameter), and a random orientation due to the spraying. The casein-based matrix embedding the fibres is assumed to exhibit, once fully cured, a Young's modulus of 5 MPa and Poisson's ratio of 0,35. The volumetric composition is obtained based on the mix design with 13% fibres (this mass fraction translates to 10% volume fraction) and an estimate of the spraying-induced porosity of 30%. All these inputs allow us to predict, according to the micromechanics multiscale model (Königsberger et al., 2023, 2024), the sought stiffness of the cellulose-casein composite with a modulus of 7.2 GPa and a Poisson's ratio of 0.24. The fibres thus considerably stiffen the casein matrix, even after accounting for the additional porosity.

The advantage of this microstructure approach is its flexibility: any changes of composition (amount or type of fibres or matrix material) can be accounted for, making lengthy experimental testing series unnecessary. Notably, micromechanics modelling can also be employed to estimate the material strength. The predicted composite stiffness and composite strength may then be used in a structural simulation using finite elements to predict the elastic deformations and the load-carrying capacity of the sprayed structures.

3.5 Sub-structure Design

The substructure must fulfil several requirements: The surface of the substructure must have a certain degree of roughness and absorbency to ensure adhesion of the sprayed material. In addition, the substructure must have sufficient inherent stability so that it can absorb the forces of the spraying process, even regarding slight deformation. To fulfil the sustainability goals of the research framework, a material of biological origin and biodegradability must be deployed. In terms of geometry of the substructure, the sizes and depth of openings and cavities must be negotiated with collision-free accessibility, the injection depth and the necessary space for the deposition of material.

4 Results and Reflection

In subsequent experimental studies two substructure strategies have been explored, fibre winding of hemp ropes and fabric tubes (see Fig. 5).

Fig. 5. Samples with different substructures

The substructures were adapted and evaluated regarding surface and surface properties, inherent stability, and application behaviour due to the fundamental geometry. A jig was built for the fibre winding process, in which the hemp ropes were stretched and wound. The focus was to achieve enough tension on the ropes to provide inherent stability so that they would not fail during the spraying process. The fabric tubes were filled with expanded clay aggregates, set, and bundled to an auxiliary construction. Both substructures were 3D scanned in their original form.

Afterwards, they were sprayed with a thin layer of the cellulose material and 3D scanned again while still wet to estimate the layer thickness distribution and coherence with the 3D simulation. The prototypes were then left to dry for 24 hours before being scanned again to assess any deformations that occurred during the drying process (see Fig. 6). This process was repeated for a second layer. The material sprayed adhered well to the substructure due to the fibre winding strategy. However, the small surface area limits the build-up of material thickness. To achieve greater thickness, the material would need to be woven more tightly or built up over more layers. A significant amount of sprayed material also passed through the structure, which can be reused. During a simple axial load test, the prototype was subjected to a dead weight of 1.5 kg. Material failure occurred at 151.5 kg, and after a constant load for one minute, buckling was visible in the centre on the right side, leading to failure (see Fig. 6).

The prototype fabric tubes also adhered well to the substrate, allowing for rapid build-up of material and achieving the desired layer thickness in just a few layers. However, the filling of the fabric tubes resulted in limited ventilation from the inside, leading to a longer drying time.

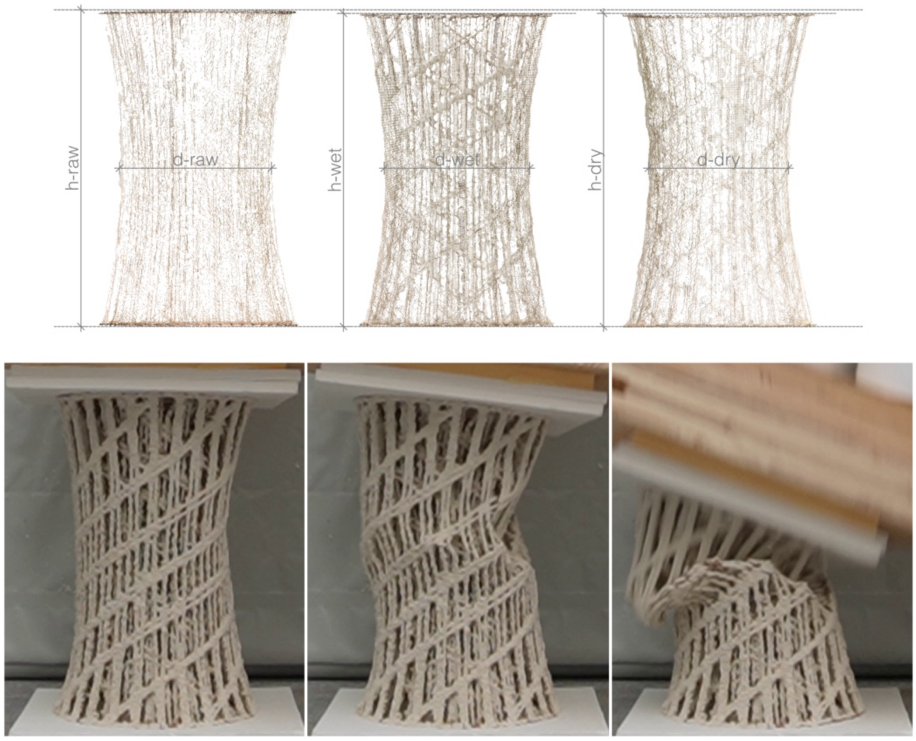

Fig. 6. Point clouds before and after the spraying (top) and axial load test (bottom)

5 Conclusion

The developed prototypes (see Fig. 7) are convincing in their aesthetic and structural performance and must now be tested on an architectural scale in the next phase. The workflow has been established as a concept and must now be further developed and evaluated in its individual components to achieve the long-term goal of an interactive and adaptive design and fabrication method.

Fundamental questions about the durability and strength of bio composites remain and can only be answered through interdisciplinary research in the future. Our demands and expectations of these new materials must also change. It seems realistic that accompanying monitoring will be necessary, as these materials are more complex and more susceptible (Thomsen and Tamke, 2022). Of course, this also limits the current usability for architectural applications, as changes in humidity affect the structural properties tremendously. One solution to this problem, in addition to the further development of the hydrophobic properties of the material, can be the integration of safety features - for example, through the redundancy of the elements or the inclusion of the substructure in the load-bearing capacity.

In the present study, a cellulose-casein mixture was used. This material would have to be exchanged and modified depending on the application. The decisive advantage of green composites lies in their versatility and adaptability to a design, which can be achieved through a specific material mixture and the orientation of the fibres tailored to the architectural geometry and its structural performance.

Fig. 7. Method applied in research-led teaching, student work

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