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Matrix application processes for RoboFelt, a system of additive manufacturing needle-felted fiber composite structures

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Abstract

The research project proposes a method for 3D printing felted fiber forms which act at the same time as reinforcement as well as a moldless form-determining agent for concrete parts. The process is twofold: In the first step fibers are densely packed and brought into the desired self-supporting shape employing a numerically controlled needle felting process. This builds on the work by Disney Research on 3D felt printing [1]. In the second step, the felted workpiece is infused with a matrix material like UHPC without the need for additional molding. This build on the Meshmould research by Gramazio & Kohler [2]. Our method allows to fabricate and reinforce complex UHPC parts without the need for molding. Most tangible applications would be in small parts such as connectors and joints. Later applications should be feasible at a larger scale employing a swarm of small to medium-sized mobile robots. The paper focuses on evaluating processes of applying a matrix to the fiber parts.

Keywords: Felting, UHPC, fiber reinforcement, digital fabrication, robots, composite materials, digital concrete

1. Introduction

RoboFelt is an ongoing research project on novel ways of using reinforced UHPC for complex forms without formwork. A robotic system is used to feed fiber fleece to a felting needle to form stable fiber elements able to act simultaneously as reinforcement and formwork. This fabrication method allows designers and engineers to control material properties such as fiber density and composite mix entering the paradigm of functionally graded materials (FGM). In this case it allows to vary functional, aesthetic and structural properties. The research is broken down into the following topics:

I. Design and engineering of a needle-felting tool for a 6-axis robot.

II. Exploration of design opportunities and constraints of the needle-felting tool (shape/fiber

layout)

III. Testing different UHPC application methods to the felted-shape.

IV. Testing structural properties of different fiber-UHPC recipes.

V. Build a design-app that allows to model: shape, fiber layout, UHPC distribution.

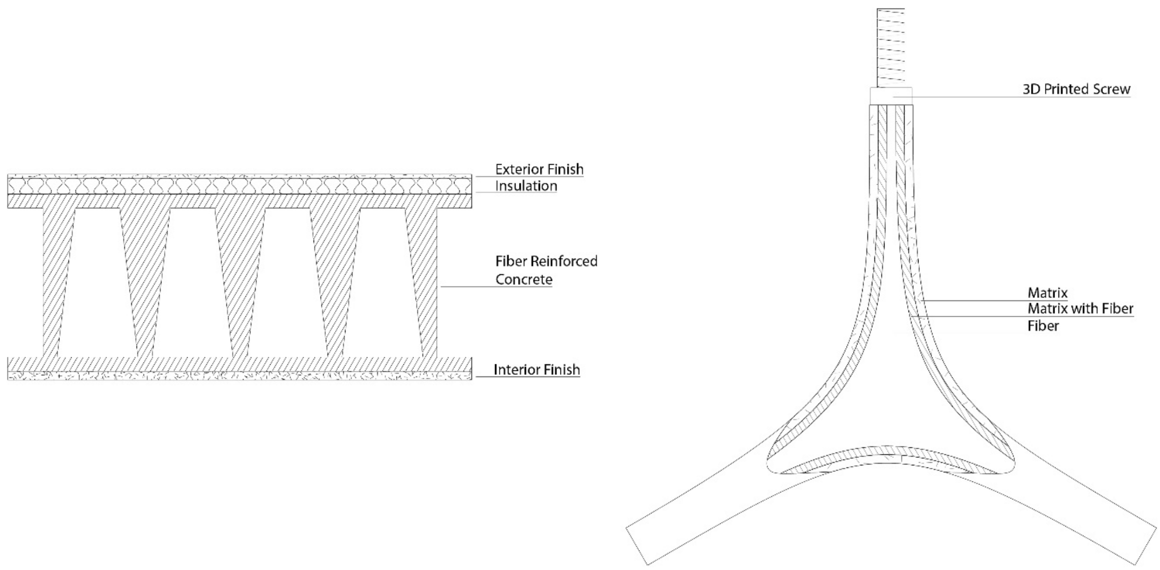
The paper will discuss mainly II. and III. and give an outlook to the future direction of the research project.

2. Design Opportunities

The RoboFelt fabrication method is being explored is two design scenarios: (A) The production of free-form walls that integrate structure, insulation, and surface finish in a single FGM (Fig.1). (B) The fabrication of complex joints for cylindric structural elements. This scenario is the main focus of this paper and therefore will be the base for the prototypes here presented (Fig. 2).

Design scenario A consists of the deposition of strands of fiber fleece that are robotically needle-felted varying the speed of displacement of our custom robotic felting actuator. This variable allows to control the fiber density in such a way that it can be impregnated with a matrix to form a composite.

Design scenario B consists of the use of a felting actuator to produce complex and precise joints of fiber fleece that, therefore, receive assembling components and are impregnated with UHPC or resins to acquire compressive strength. The robotic tooling allows the control of fiber orientation and distribution to respond to the required forces within each joint and in the overall structure.



Figures 1 and 2: Detail of material distribution in a wall horizontal section

3. Composite Matrix Application

The goal of RoboFelt is to acquire control of material distribution of non-oriented fibers in combination with a matrix and develop a fabrication method for complex forms free of economically prohibitive formworks for casting. At the current stage, our aim is to identify processes that could be built into a robotic tool. A series of needle-felt actuator prototypes have been developed.

The ability to control the fiber density and areas of matrix application offers the possibility to have a FGM. Such a FGM exhibits better performative behaviour as well as offering a new level of formal freedom for designers (architects, structural engineers, industrial designers). Traditionally architectural systems are composed of parts that respond to a hierarchy. Instead of systems and subsystems, our proposal's goal is to vary function within a continuous material. In addition a FGM uses materials more resourcefully than traditional construction, saving material costs and diminishing the impact of the construction industry in the planet's resources and environment.

4. Composite Matrix Application Processes

In the scope of this paper we look at the process of impregnating the needle felted piece with a matrix to yield a composite material. We tested 3 different processes which do not require a bespoke formwork for complex geometries: (I) Shotcrete, (II) Infusion and (III) Immersion.

4.1. Shotcrete Matrix Process

Sprayed concrete exists in Germany since 1920 [3], especially in tunnel construction, rock stabilization and strengthening of existing structures [4]. The method is to spray concrete with compressed air through a nozzle in such a way that it self-compresses when it reaches a surface or mesh. One of the advantages of this method is to produce complex forms with lightweight formworks, avoiding the use of expensive and complex wood formworks. The traditional application of shotcrete involves a skilled operator that sprays continuous concrete at a surface from a distance. It allows fast and cheap construction of complex form but lacks control of material thickness and produces very rough surfaces that require finishing after.

A digitally enabled version of this technique is being developed at TU Braunschweig, where a concrete spraying robotic tool and a 5 degrees of freedom CNC controlled surface are assembled on two portals and are free to move in a workspace of 9m x 17m x 3m [5].

We used a scaled down shotcrete process by applying the matrix material via a handpump onto the surface of the fiber samples.

4.2. Infusion Matrix Process

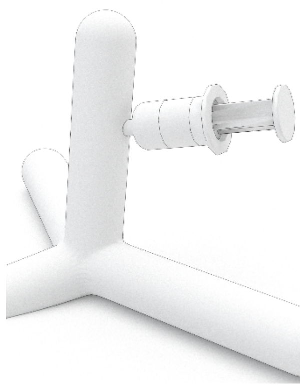
Infusing or injecting a matrix into fiber or aggregates is not very common with concrete. Injection methods are sometimes used in concrete crack repair jobs. We propose a process where concrete is infused directly into a relatively dense fiber pack forming a blob of composite. This process is repeated till all blobs join up to form an overall stable composite structure. This infusion application could be digitized by a robotic tool method where the placement and distribution of blobs is controlled numerically. It would allow a digital and more precise way of material organization and we tested this process through the use of syringes inserted inside the felted form.

4.3. Immersion Matrix Process

Immerging formwork in fluid materials has a long tradition in ceramic production. Hydrophilic formworks, like plaster, are immerged in liquid ceramic for a short period of time and removed. Its walls are, then, impregnated with a layer of less fluid ceramic that shrinks during drying, releasing itself from the formwork and allowing it to be reused, permitting economies of scale.

Our immersion matrix application inverts the position of the formwork from the form negative to a form positive, resulting in a process of lost-formwork / partial composite structure. A robotically felted fiber form is immerged in the matrix material and thus impregnated, gaining additional compressive strength.

Table 1: Diagrams of Composite Matrix Application Processes

4.1. Shotcrete Matrix Process	4.2. Infusion Matrix Process	4.3. Immersion Matrix Process
		

5. Material Samples

To evaluate the feasibility of our proposed fabrication methods, we produced a series of specimens testing the three previously discussed matrix application processes with two different materials: cement and plaster which act as surrogates for UHPC. In a later stage, a UHPC recipe has to be developed to match the found process and composite requirements. At this stage, the more relevant characteristics are the viscosity and setting behavior of the matrix material.

Shotcrete Matrix application (4.1) was performed by spraying cement and plaster with a hand pump to deposit material onto the surface of the felted form.

Infusion Matrix application (4.2) was performed by injecting cement with a syringe into the felted form. In these two methods, the volume of cement and plaster applied varied: In the shotcrete method, we use three times less cement or plaster than in the infusion method.

The shotcrete process favored, during application, more homogeneous surface finishing, distributing material in a constant way. The infusions method had a different approach: instead of the constant application of cement or plaster, it tended to have a more controlled way to posit the syringe and inject material inside the fiber form.

The immersion matrix application (4.3), was done with different immersion times. Both on cement and plaster, felted forms were immersed in a highly fluid mix for 10 and 20 minutes to test how deep the matrix gets absorbed into the fiber form.

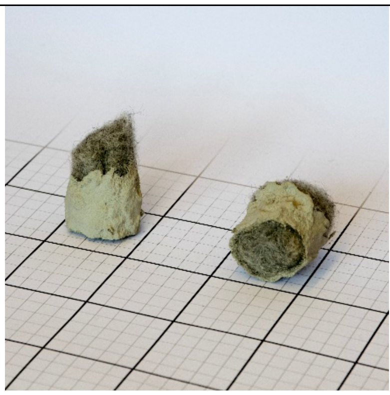
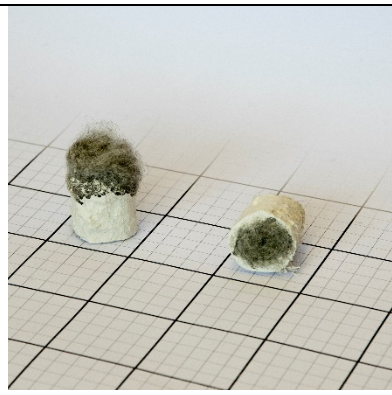
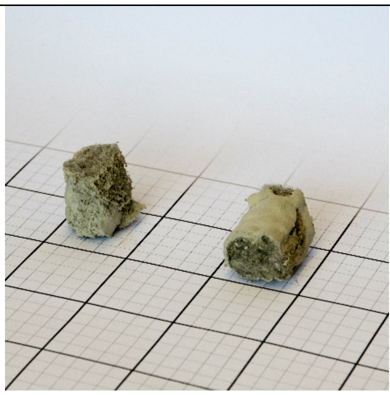
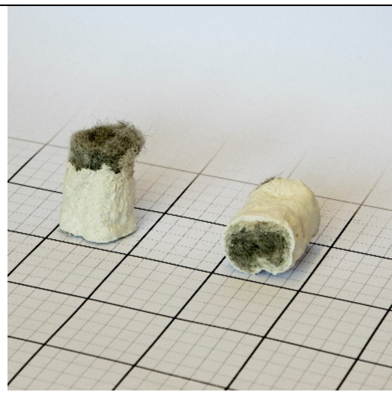
The viscosity of the concrete and the plaster mixes are the key parameters here. In all methods, a high viscosity is required to apply the matrix. However, since there's no outer formwork to hold it while it sets, a degree of formal stability is necessary to bond with the needle felted form.

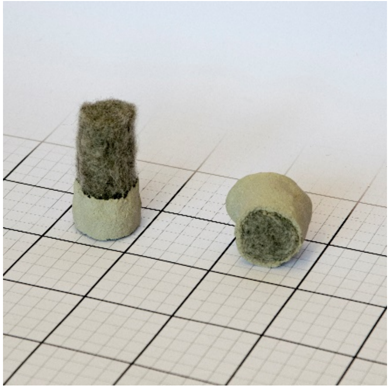
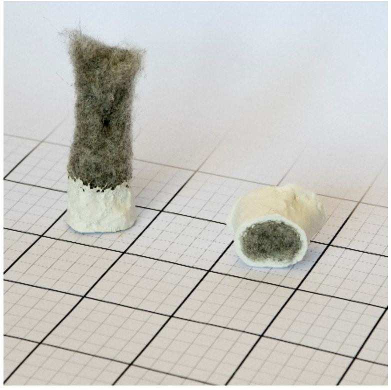
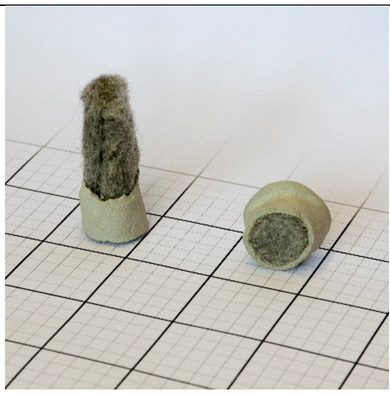
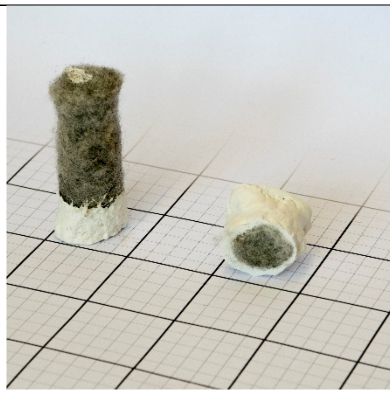
The materials used here were selected keeping in mind that at this stage our research is focusing on the fabrication method and not in the material behavior necessarily. In the future, cement and plaster should be substituted by UHPC or resins. Also, the fleece can different form natural, synthetic, metallic, and mineral fibers. Although there are studies of using sheep wool for mineral reinforcement [6].

6. Section Analysis of Material Distribution

As tests, 8 specimens were produced, as shown in Table 2.

Table 2: Relation between Methods and Materials

Method / Material	Cement	Plaster
Shotcrete Matrix Application		
Infusion Matrix Application		

Immersion Matrix Application (10 minutes)		
Immersion Matrix Application (20 minutes)		

A qualitative analysis shows that there are basically 3 material distribution variations, as shown in Table 3:

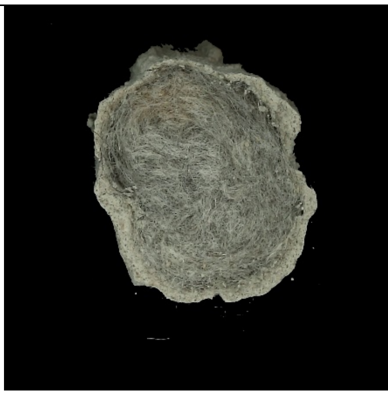
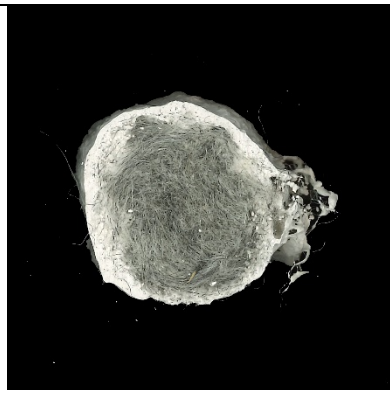
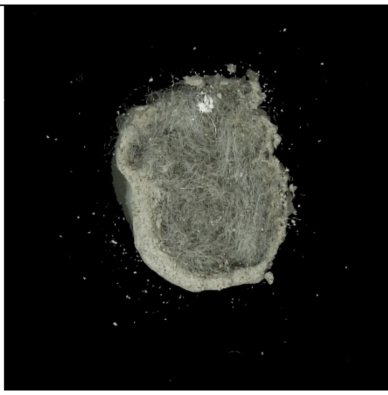
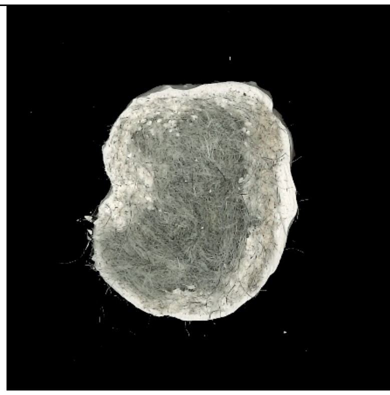
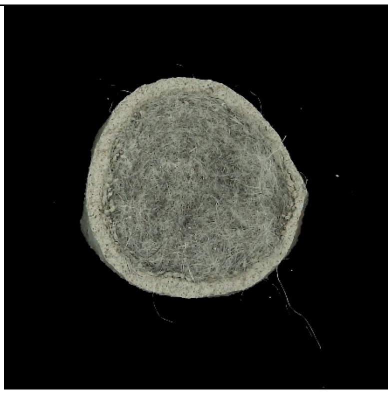
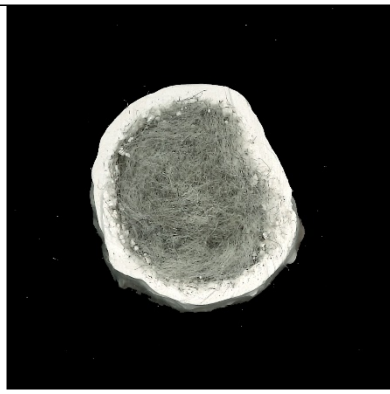
(A) On the outside of each section, there’s a layer of pure matrix material with variable thickness. Made out of UHPC this could take the function of protecting the fibres form corrosion and weathering processes.

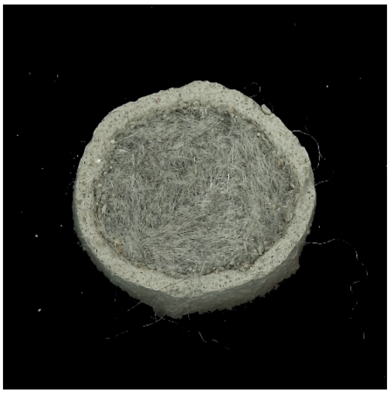
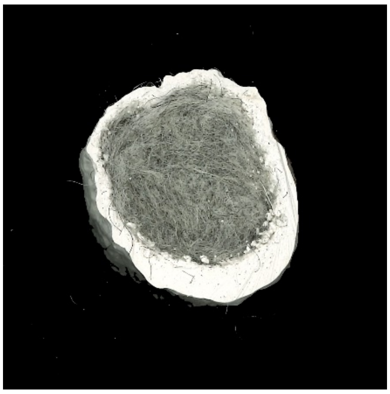
(B) Then comes the composite layer, where fiber and matrix form the desired bond. The thickness of the layer also varies. The goal it to hit the desired composite thickness and strength in each part of the piece.

(C) In the center of each section, there’s pure fiber core not effected by the matrix. This helps the form to be stable before and during the matrix application process.

The results show that there’s a heterogeneous distribution of material. While the density of fibres can be precisely controlled during the robotic needle felting process, the quality and thickness of the composite zone is a function of this density and the process parameters of the matrix application.

Table 3: Sections of specimens

Method / Material	Cement	Plaster
Shotcrete Matrix Application		
Infusion Matrix Application		
Immersion Matrix Application (10 minutes)		

Immersion Matrix Application (20 minutes)		

To calibrate the density of needle felted material for the matrix infusion process, a series of differently dense specimens were tested, as shown in Figure 3:

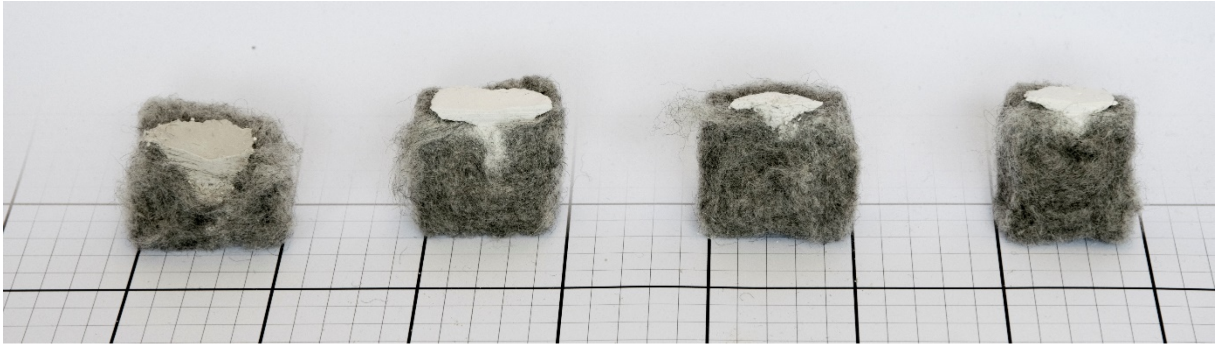


Figure 3: Sections of specimens of felted fiber. From left to right 0.032g/cm3, 0.064g/cm3, 0.096g/cm3 and 0.128g/cm3. All of them infused with the same amount of plaster

As a proof of concept, a joint was felted and immersed for 20 minutes in cement. Two of its ends were protected from the matrix to consider posterior felting. In one of its ends, a rigid screw connector was felted into the form to prove the possibility of integrating mechanical fixtures.

6. Discussion

The results are promising as they indicate that a relatively thin and controlled layer of composite can be created in a precise way with a needle-felting actuator on a 6-axis robot.

All tests indicate that the needle felted forms have to be better tuned in their density to balance precomposite stability and ability to absorb matrix material in the required way. This calls for further research on modelling, simulating and robotically fabricating highly differentiated felt density taking in consideration functional and structural performance.

For the next step when building prototype tools for matrix application the following has to be considered:

Shotcrete: it would be necessary separate the felting and matrix application into two independent processes and robotic actuators. The reason is that spraying the concrete makes the work environment wet and dirty. This process seems to be equally suited for on-site and off-site construction.

Infusion: it shows high potential for carrying a tool along with the needle felting tool to infuse the form in a bitwise fashion directly following the felting. It has promising scalability functions and seems suitable for on and off-site construction. From the processes studied it exhibits the best potential for a fully digital process. We propose the integration of needle-felting and matrix application in the same actuator. It allows the best digitalization process, enabling full control of material distribution in a blob/voxel fashion. Also, we are considering swarms of small robots with complete actuators because it offers great scalability and is good for on-site and off-site construction.

The Immersion matrix application process shows great potential for many small parts and building components in a off site prefab environment.

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