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Robot-aided rearrangement of steel fibres in UHPFRC via magnetic forces

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Abstract

The undirected distribution of steel fibres in pre-fabricate concrete elements is of substantial nature. The goal of this investigation is to increase the local mechanical properties of specific concrete elements by controlling the alignment of the fibres according to the flow of forces using robots. The paper will present theoretical consideration and experimental research of the robot controlled interaction between magnetisms and the steel fibre orientation in a translucent gel as a substitut for freshly cast fibre reinforced concrete.

The predefined path of the robot was controlled via movement parameters acceleration and velocity. The end effector of the robot arm was implemented with ultra-strong neodymium magnets of different dimensions and polarity. The repeatable path of the end-effector ensured reproducible interaction between the force fields and field lines of the different magnets, the geometry of the tested fibers and the geometry of the mould. The desired micro-overlap of parallel-orientated fibres in the tensile zones could be achieved by using sets of magnets mounted on the end-effector of the robot: They were aligned due to their specific characteristics and the particular choice of the fibres. Using the effect of moving these sets on the outside of the moulds in a rotary way, the concentration of fibres affected by the magnets could be increased drastically.

Keywords: Robotics, UHPFRC, magnetism, fibre orientation, digital production, parametric design, mass customization

1. Introduction

UHPFRC (Ultra-High Performance Fiber Reinforced Concrete) as a composite consists of two ingredients providing two properties: The high compressive-resistance of the matrix and the tensile strength of the fibers. Since every structural member is submitted to specific local forces, whereas the distribution of fibers is extensively undirected, conventional UHPFRC members contain much more fibers than structurally needed. When looking at the conventional and undirected distribution of UHPFRC, only one third the undirected distribution of fibers contribute to the tensile strength of the composite. However, the widespread production processes facilitate this supersaturating of steel fibers of fiber-reinforced concrete: In the hope of a uniform distribution, fibers and matrix are mixed extensively before being poured into the moulds. In order to guarantee a certain minimal concentration of activated fibers in the cast components, the amount of all fibers must be increased, accompanied by the risk of balling of the fibers during the mixing process. Novel elements such as shells providing fibers aligned in zones where they are effectively needed would reduce the waste of fibers drastically. Accordingly, the entire member could be designed in a more effective, filigree and sustainable way. Furthermore the robotic post-modeling of reinforced areas before hardening could replace the complex pre-fabricated reinforcement structures.

After the author investigated the principals of magnetic rearrangement of steel fibers in UHPFRC in 2014 [1], the present paper introduces a method that aims to rearrange the distribution and orientation of steel fibers in freshly cast UHPFRC by using robots in order to guarantee repeatable and accurate results.

The initial impetus to take on the topic of this specific research arose from investigations on fingerjoints for modular shell structures in the framework of the German Research Foundation's priority program "Concrete Light"[2]. Here, thin plates (300 x 200 x 15mm) as specimens for prospective thin walled shell structures made from UHPFRC were developed. The positive results of examined tests of bending moments, normal and shear should not disguise the fact that the area of the joints can still be improved, not only on the geometric but also on the material level (Figure 1, middle and right). Using the conventional way of casting, the distribution of steel fibers of the finger joint is according to the flow of the liquid matrix and not according to the assumed flow of forces of the member (Figure 1, left). As a consequence the new research is to manipulate the local material properties accordingly to the local flow of forces in order to eliminate structural weaknesses not only of the frontal connections but also of the tensile zones and laminar region of the shell structure elements.

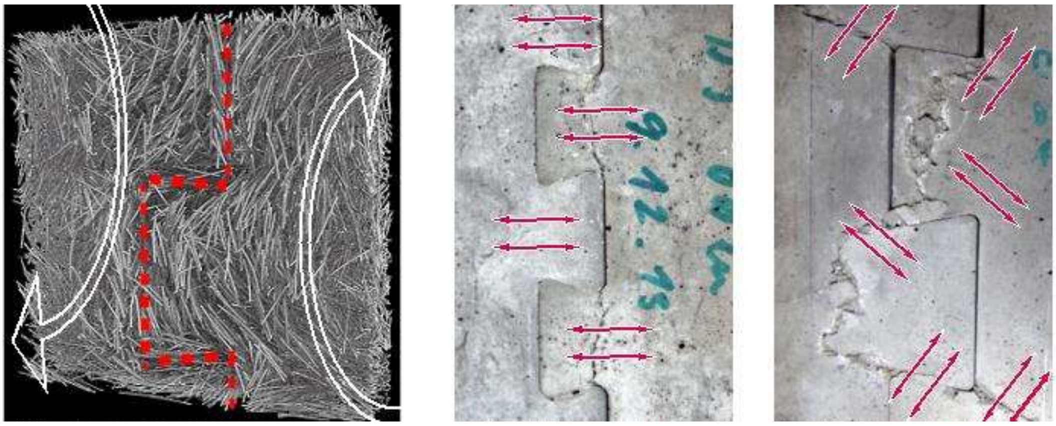

Figure 1: Micro-CT scan (left), Cracks after bending test show desired direction of the fibers parallel to the tensile force(middle), Cracks after compression test show desired direction of the fibers perpendicular to the shear force (right).

Coming from the attempt to use the benefits of modern CAD and FEM tools for the development and design of individual bulildings and building elements according to the flow of forces and constructed from UHPFRC (Figure 2), the implementation of the descibed method into the production asks for an automised process. The main focus of this research was to define the basic parameters for this process.

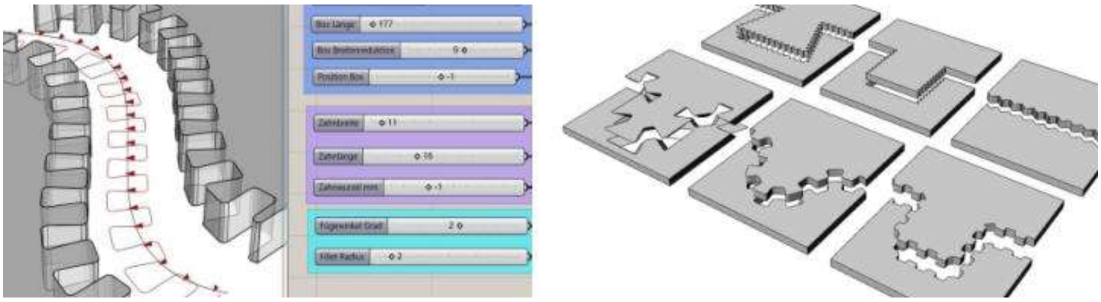

Figure 2: Parametric model of finger joints along a specific curve (left), different phenotypes of the same parametric model (right).

2. Related work and techniques

In the following the related work and techniques are subdivided into two sections: The method to use magnetic forces to reoriented steel fibers and the use of CNC machines and robots for processing individual workpieces.

2.1 Using magnetic forces to rearrange steel fibers in cementitious materials

The most elaborated work regarding the influence of magnetic forces on ferromagnetic fibers in the field of construction engineering represents the dissertation of Prof. Dr.-Ing. Stefan Linsel published in 2005 [2]. His main focus was the numerical and experimental investigation of the general feasibility to turn and pull isolated steel fibers. Having also tested specific prototypes, he regards the targeted application of the phenomenon as a worthwhile research and task for further development.

Besides this preliminary work, the company Mapei distributes magnetically parallel oriented steel fibers, but the intension here goes in exactly the opposite direction: This magnetic orientation should secure a more homogenous distribution of fibers in concrete and not provide a concentration.

The controlled inflow of the concrete into the mould - and along the orientation of fibers - can in fact increase the degree of efficiency of the fibers, but this technique is quite limited for the following three reasons: The geometry of the mold that determines the flow of fresh concrete often does not correspond to the flow of forces of the loaded component. In addition, all fibers are still distributed in the full section of the component, whereas a concentration of the fibers in the areas subjected to tensile forces is desirable in order to increase the resistance of the member in those highly stressed areas. Finally, a verification of the assumed distribution within the framework of quality management is expensive and time-consuming.

2.2 Robotic controlled processes of individual workpieces in architecture

There are many references of a production process using 3D-CAD/CAM systems for controlling 6-axes-robots. However, these processes were traditionally reserved to goods of mass production in the fields of all industries like aerospace and automotive. The latest development here is the Industry 4.0, which is distinguished by an environment of customization of products under the conditions of high-flexibilized mass-production. This required automation technology is improved by the introduction of methods of self-optimization, self-configuration, Self-diagnosis, cognition and intelligent support of workers in their increasingly complex work.
The attempt to introduce digital and CNC-based technologies into the sector of building construction, where members need to be produced as prototypes or in small runs, arose progressively in the last twenty-five years. In this field of architecture, Frank O. Gehry's office began using CAD/CAM processes in 1989 to develop and then test the constructability of a building system for the Disney Concert Hall. One of the pioneers in Europe is the research unit Gramazio & Kohler for Architecture and Digital Fabrication, located at the Department of Architecture at ETH Zurich, established in 2005.

3. Setup for the experimental research

The test setup for the experimental research consists of four main components: The translucent matrix as the substitute for the UHPC (Ultra-High Performance Concrete) for the preliminary tests, the UHPC itself, the steel fibers, the translucent moulds and the magnets.

3.1 Matrix (Substitute and Concrete)

Substitute: As a translucent substitute with similar viscosity for still liquid UHPFRC, medical ultrasonic gel was confected and used in order to achieve immediate visual control over the influence of the magnetic fields on the movement of the fibers. The mixing ratio of that substitute was set to 55 pbw gel on 100 pbw water. This mixing ratio simulated best the spreading properties of the proposed FK1-2.5 fine grain UHPFRC. The viscosity of the mixture was stiff enough to prevent the fibers from sinking, although it tends to increasing demixing. The complex viscoelastic behaviour and particle sizes of the UHPC were not yet taken into account and are subject of further studies.

Concrete: The initially chosen concrete was due to its convenient rheological properties an UHPFRC (Ultra-High Performance Fiber Reinforced Concrete) containing 1 to 2,5Vol% of fibres. Nanodurr® Compound by Dyckerhoff GmbH, a premium binder that already contains pozzolans based on synthetic silicic acid for hydration control, was used.

3.2 Fibres

Being made of steel, the choosen micro fiber shows reaction to magnetic induction and is able to form coherent, free-standing strands under the influence of magnetic fields. The used type is distributed by KrampeHarex®. This fiber was choosen due to its great ability to show the magnetic field lines in a high resolution.

Type	Description	Name	Lenght (mm)	Ø (mm)	Shape	Material-No.	Tens. strenghth (N/mm²)
F1	micro fiber	DM 6/0,17	~9,0	0,15-0,22	round	1. 0620	min. 2100

Table 1: Properties of fibers F1

3.3 Mould

The dimensions of the mould were 250 x 350 x 20mm. It was mainly made from pellucid sheet material that had a thickness of 5 mm (Figure 4, left). It was assembled using glue and machine screws made of non-magnetic material. Since the adhesive force of the magnets is antiproportional to the distance between the magnet and the fibers (Figure 6, left), the wall thickness of the mould should be minimised as much as possible.

3.4 Magnets

Permanent neodymium magnets (NdFeB) of different dimensions and polarity were chosen for the end effecor (Table 2). They are the strongest type of permanent magnet commercially available and their greater strength allows the use of smaller and lighter magnets for a given application. In this research the small dimensions but strong and concentrated magnetic fields of these magnets appeared to be positive for the control of the very short fibers in particular.

Type	**Form**	**Magnetization Quality**	**Dimensions (mm)**	**Direction of magnetization**	**Adhesive Force (N)**
M1	Square block magnet, 3pcs	N42	15 x 15 x15	axial, top and bottom	170 each
M2	Square block magnet, 3pcs	N45	30 x 30 x 30	axial, top and bottom	600 each
M3	Rectangular block magnet	N40	80 x 50 x 50	axial, front surfaces	2800

Table 2: Properties of magnets M1, M2, M3

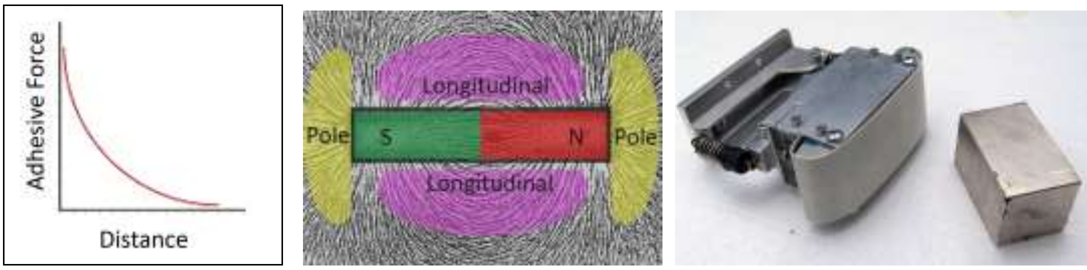

Figure 3: Antiproportional relationship between adhesive force and distance (left), perpendicular field lines at poles and longitudinal ones in between (middle), magnet M3 and end effector (right)

3.6. Robot

The used robot was an UR5, produced by Universal-Robots (Figure 4, middle). It has a payload of 5 kg and a reach radius of up to 850 mm. It has 6 rotating joints and a repeatability of +/- 0.1 mm. The speed of all joints is 180°/s. The typical speed of the tool is 1 m/s.

3.7. End effector

The different magnets were mounted in a custom-made end effector mainly made from aluminum (Figure 4, right). It consists of a suspended base for the magnet holder. In order to compensate potential unevenness of the moulds, the end effector is equipped with two springs that allow a suspension travel of 25mm. The magnets itself are imbedded in a slide with runners on both sides in order to prevent end effector to get stuck on the moulds.

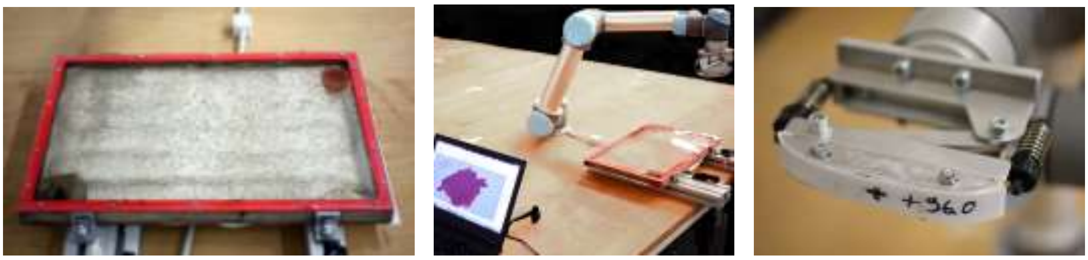

Figure 4: pellucid mould (left), setup with robot (middle), end effector with magnets M1 (right)

3.8 Software

The used software to controll the UR5 was McNeel`s Rhino3D and its parametric design tool plug-in Grasshopper. The Grasshopper plug-in Scorpion was used as an robotic controller for the industrial robot UR5. It contains tools for the generation of robotic programs from paths, inverse kinematic solver for universal robots and direct upload to the robots through TCP/IP.

4. Experimental research

The presented first set of tests cover the investigation of robot-aided rearrangement of steel fibres in a substitute for UHPFRC via magnetic forces. The initial aim here was to use a substitute for the UHPFRC in order to allow visual control over the results. The seven different robot path shown here were created using CAD software as described above. The path of the robots could be verified as an offline-simulation in Scorpion in order to control the intended path (Figure 5). All tests were executed with the same setup regarding the mould, the type and number of magnets (three magnets M3), speed of the robot (.35m/s, apart from Test 8) and the mix of the substitute (diluted supersonic gel with 2,5Vol% of fibres type F1).

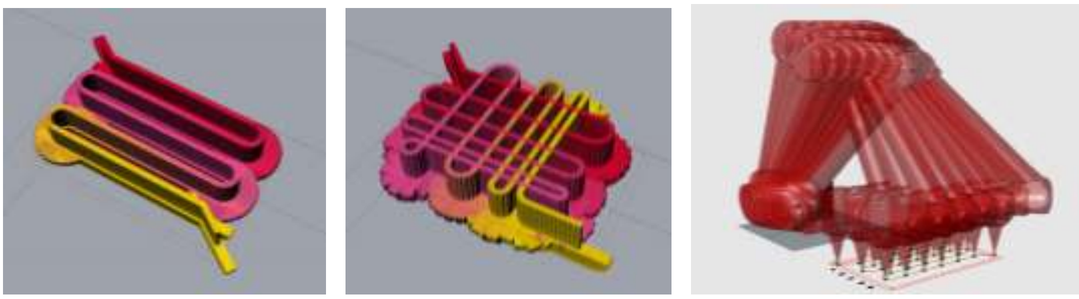

Figure 5: Simulation of the path of Test 1&2 (left, middle), Offline simulation using Scorpion Virtual Robot (right).

4.1 Test 1: Five different distances between the magnets and the substitute

This first Test was executed in order to investigate the effect of different distances between the magnets and the substitute. The distances were increased stepwise up to 8mm (Figure 6, left). Adding the thickness of 4mm the mould itself, the entire maximum distance from the matrix was 12mm. The result shows according to the linear increasing distance of the magnets an antiproportionaly decreasing concentration of the strands (see Figure 3, left). The lower speed of the robot when turning from one straight stand to the next caused a higher concentration of fibres in this specific area (red suare, Figure 13, left).

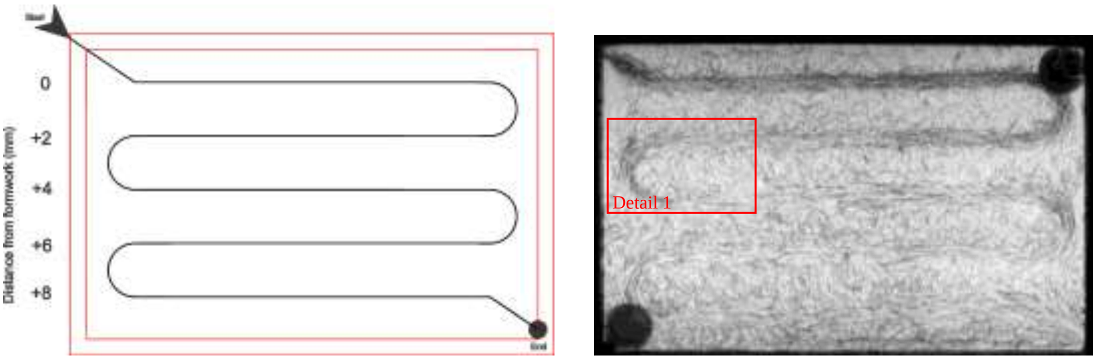

Figure 6: Path of the robot (left), Result after two runs (right).

4.2 Test 2: Five different numbers of repetitions of the same paths

Test 2 was executed as a further stage of Test 1. Here, the magnets are not only touching the mould as in Test 1, upper row “0”, but the straight paths were also repeated gradually from one to five times. Accordingly, the result is an increasing concentration of the strands (red arrow in Figure 7, right,).

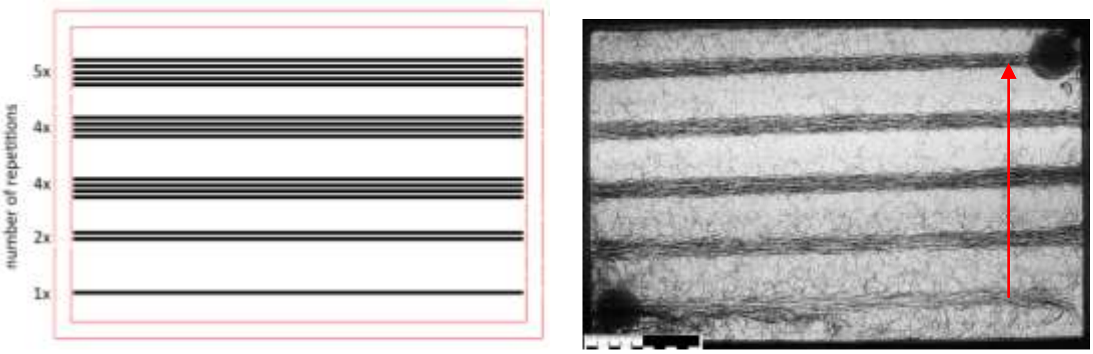

Figure 7: Path of the robot (left), Result after one run (right).

4.3 Test 3: Crossing the paths in a grid of different sizes

The aim of Tests 3 and 4 was to create intersection of two crossing strands. The idea here was to increase the flexural strength and resistance to complex bending moments as they occur in members that are exposed to biaxial stress such as plates and ceilings. Here the paths of the end effector were crossing while touching the moulds.

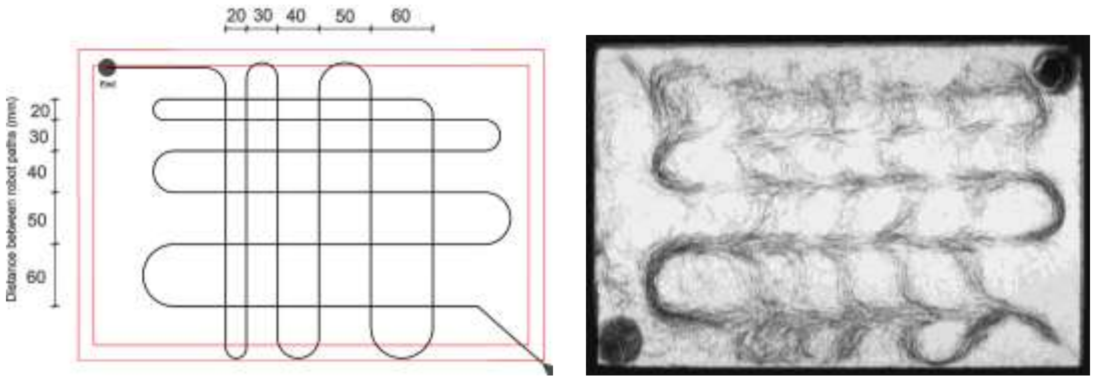

Figure 8: Path of the robot (left), Result after one run (right).

4.4 Test 4: Crossing the paths in a distance of 5mm in a grid of different sizes

In contrast to Test 3, the result of Test 4 showed the result of the different perpendicular crossing of the two paths on two different levels: the first one touching the mould (distance=0) and the second and perpendicular paths crossing in a distance of 5mm (Figure 9, left)

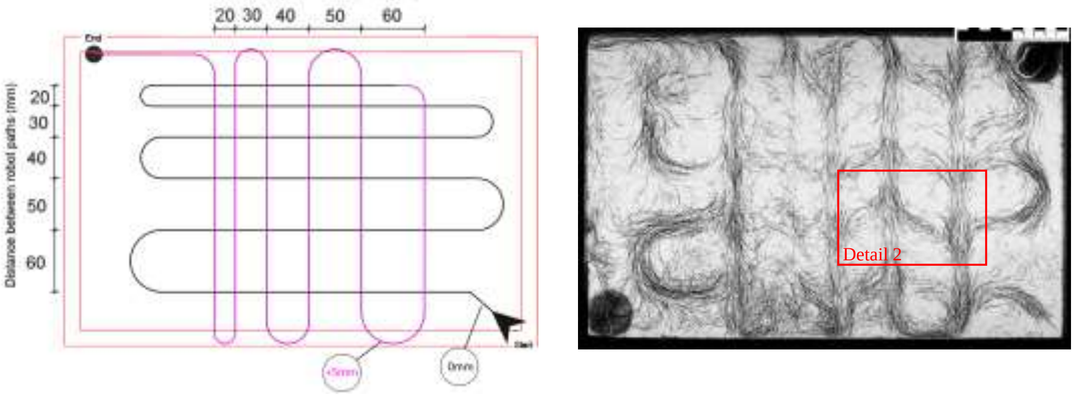

Figure 9: Path of the robot (left), Result after one run with Detail 2 (right).

4.5 Test 5: Gathering fibers using rotary paths of different diameters

While Tests 1 to 4 focused on the creation of strands and its potential to cross each other in order to create mingling of the fibres, Tests 5 and 6 investigated different ways to accumulate a bigger number of fibres from a larger area in order to create more compact strands. Therefore, the robot executed two distinct movements, each of those in two different proportions. This first attempt was to gather fibres from a certain diameter in a rotary way. In doing so the last robot joint and accordingly the end effector was fixed. Path 3 in Figure 10 shows a straight path and in contrast to the rotary path 1&2

much less accumulation of fibres. It is remarkable that Path 1 in particular shows a concentration of fibres on the side where the connecting moves between the rotations were executed (red mark).

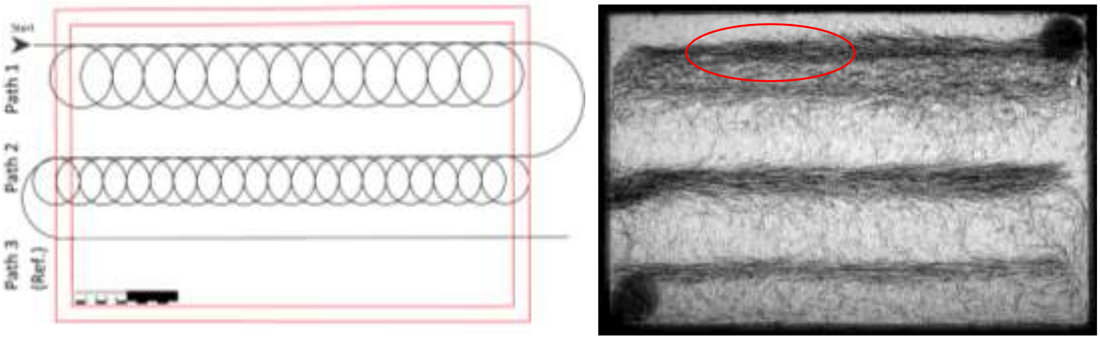

Figure 10: Path of the robot (left), Result after one run (right).

4.6 Test 6: Gathering fibres using “panicle-like”

This second attempt was to collect proximate fibres by running "panicle-like" paths (Figure 11, left). Therefore, the end effector pulled the nearby fibres into the intended area of the strand just like a broom is handled when cleaning a floor: Collecting alternately from the left and right side towards the center, while continuously moving forward. The result (Figure 11, right) shows that the area around Path 1 is less saturated with fibres than around Path 2. The figure on the right side shows the result after running five additional repetitions of straight paths as executed in Test 7.

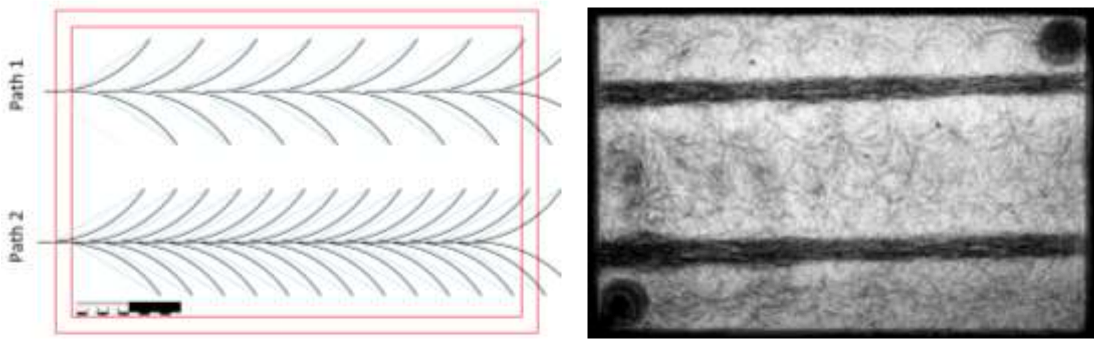

Figure 11: Path of the robot (left), Result after one run (right).

Test 7: Five repetitions of straight paths

Test 7 served as a comparison for Test 6. Here, comparable to the first strands in Test 2, five repetitions of straight strands were executed but - in contrast to Test 6 - without a previous collecting of fibres. A successive agglomeration of fibres along the repeated robot path was observed. The area that was beyond the area of the magnetic field was not effected (red marked area, Figure 12, right).

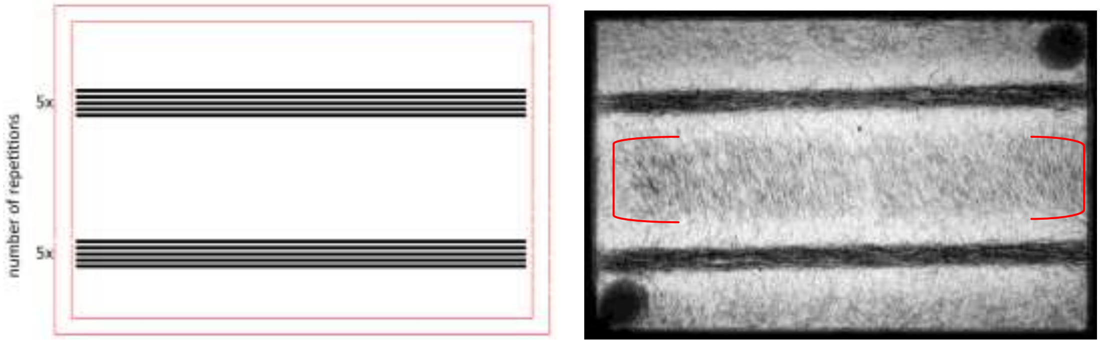

Figure 12: Path of the robot (left), Result after one run (right).

4.7 Test 8 four different velocities

For Test 8, different velocities of the end effector from 0.1 to 1.0 m/s were introduces. The results are similar to Test 1, were the magnets were run on different distances to the fibres.

Figure 13: Path of the robot (left), Result after one run (right).

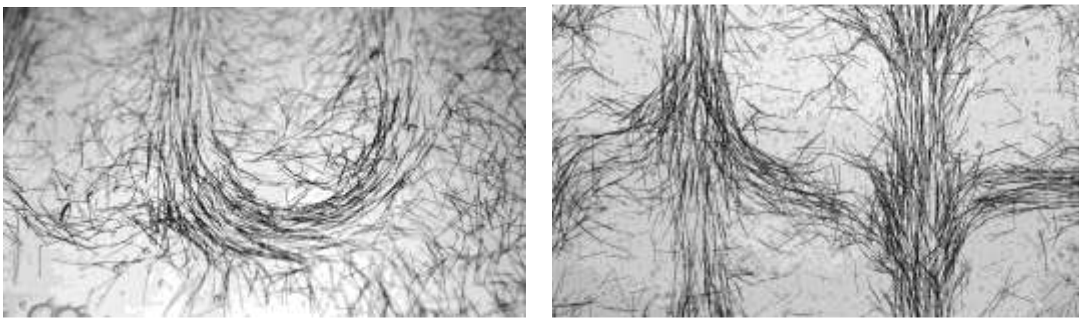

Figure 14: Detail 1 of Test 2 (left), Detail 2 of Test 4 (right).

5. Validation check of the method using UHPFRC

In this next step the insights gained in this research using the substitute were transferred to the matrix UHPFRC. Therefore, several robot-aided tests from the series above were executed in order to compare the behavior of fibres in UHPC with the results of the preliminary tests using the substitute for the concrete. The machining procedures was performed while the right after mixing the concrete in order to take advantage of the most liquid state of before hardening. The time slot for the treatment was around 15 minutes without using a retarder.

5.1 Test 1

Applying the longitudinal field lines of a set of three magnet M2 (table 2) on a distance of 4mm to the still liquide UHPFRC showed a distinct concentration of the fibres F1(Figure 15, red marks). The plate was 15mm thick and cut perpendicular to the robot path as shown in 4.1, Test 1.

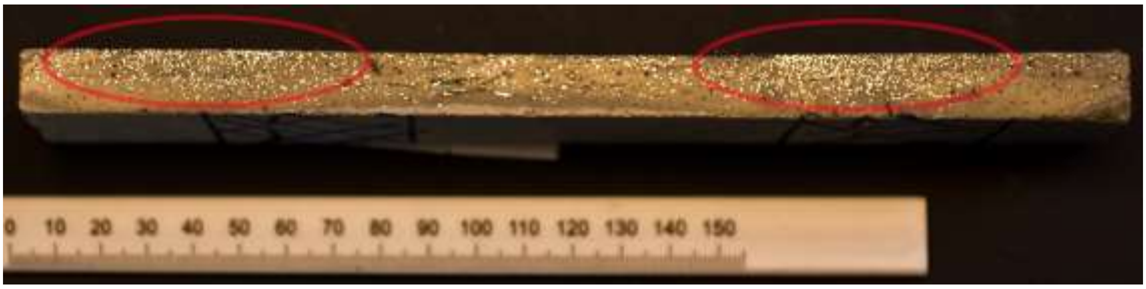

Figure 15: Microsection of plate P1

5.2 Test 2

Applying the poles of the same set up showed a distinct concentration of the fibres F1 (Figure 16, red marks). The plate was 20mm thick and cut perpendicular to the robot path as shown in 4.1, Test 1.

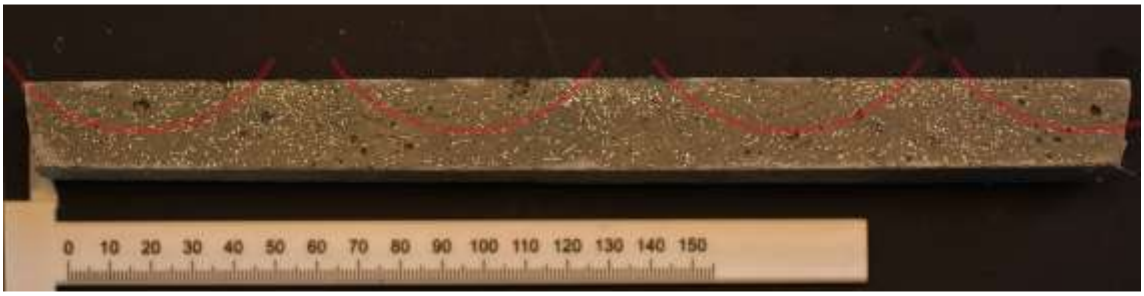

Figure 16: Microsection of plate P2

5.3 Transferability of the results of the substitute to UHPFRC

Since the viscosity of the used substitute and UHPFRC differ, the results and parameters of the preliminary test executed in Section 4 could not be transferred to UHPFRC. However, these tests were helpful for the investigation of the basic parameters and mechanisms of the rearrangement of steel fibres via magnetic forces. In fact, the main difference between the gel and the UHPFRC is the viscosity: The intensity of the magnetic field is not influenced by the viscosity or density of different materials. Nevertheless, the higher density od liquid UHPFRC will not simply need higher magnetic forces to allow embedded fibres to turn or move. Rather higher magnetic forces can only be realized using bigger magnets with more voluminous fields. Consequently these larger fields will create broader and not as concentrated strands as smaller magnets were able to create in a matrix of lower viscosity, as shown in Section 4.

6 Conclusion

The method of rearrangement of steel fibres in freshly cast concrete was executed in an automated and repeatable way using an industrial robot. Preliminary tests using translucent substitute showed principal relations and parameters of the method, which could be verified and compared to the results of tests treating UHPFRC. The mechanical benefit of the described treatment will be subject to further investigations. The application of this method may lead to a variety of novel structural members providing fibers aligned in zones where they are effectively needed. Accordingly, every member such as shell elements or any other simple or complex structure could be treated individually and thus be mass customized in a more effective and filigree way. Furthermore, the post-modeling of reinforced areas before hardening could support or even replace the complex pre-fabricated reinforcement structures. Hence the amount of steel as a finite raw material as well as a major cost driver of this composite (30%-45% total cost of UHPFRC, using 2 Vol.-% fiber content, [4]) could be drastically reduced.

References

[1] Ledderose L., *Preliminary Investigations for Magnetic rearrangement of Steel Fibers in UHPFRC. Proceedings of the IASS-SLTE 2014 Symposium*, 2014.

[2] Budelmann H. and Kloft H., *DFG Forschungsantrag - Entwicklungen neuartiger Verbindungen für geometrisch komplexe Flächen und Stabtragwerke,* Braunschweig, 2011.

[3] Linsel S. *Magnetisches Positionieren von Stahlfasern in zementösen Medien,* Berlin, 2005.

[4] Schmidt H. et al., Deutscher Ausschuss für Stahlbeton, Sachstandbericht Ultrahochfester Beton, 2010; p.10