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Preliminary Investigations for Magnetic rearrangement of Steel Fibers in UHPFRC

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Abstract

The undirected distribution and orientation of steel fibers 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 position and orientation of the fibers according to the flow of forces. The paper presents theoretical consideration and experimental research of the interaction between magnetisms and the steel fibre orientation in a substitute for freshly cast fibre reinforced concrete. The experimental reseach is understood as preliminary assessment for the proposed application material UHPFRC.

Keywords: UHPFRC, fiber orientation, magnetism

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 more fibers than structurally needed. 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.

The present paper introduces preliminary tests for the development of a method that aims to rearrange the distribution and orientation of steel fibers in freshly cast UHPFRC. 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"[1] (Figure 1). Here, thin walled shell structures made from UHPFRC capable to transfer bending moments, normal and shear forces were developed. The positive results of examined bending tests 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, left). Thus the new attempt is to manipulate the local material properties accordingly to the local flow of forces in order to eliminate structural weaknesses of the joints.

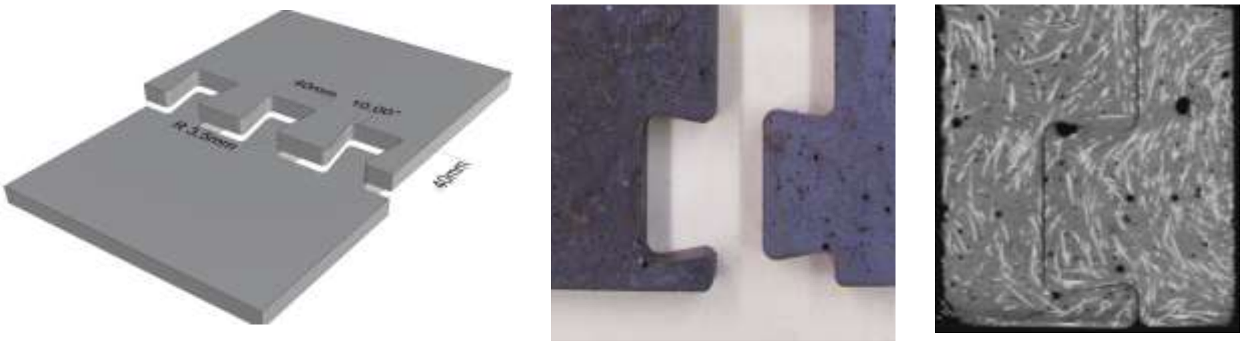

Figure 1: fingerjoints for modular shell structures (left), detail fingerjoint (middle), chaotic fibre distribution, micro CT-scan of the fingerjoint (right).

The benefits of this method are not limited to the specific application it was conceived for. Rather, it 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 designed 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, [3]) could be drastically reduced.

2. Related work and techniques

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.

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 UHPRC, the steel fibers, the translucent moulds and the magnets.

3.1. Matrix

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.

3.1. Fibers

Four different types of steel fibers were investigated: micro wire fibers (type F1&F2) glued fibers with hooked ends (Type F3) and corrugated fibers (Type F4) (Figure 2&3). Being made of steel, all fibers show reaction to magnetic induction and are able to form coherent, free-standing strands under the influence of magnetic fields. The glued fibers were seperated before mixing. Except type F2 (unknown distributor), all fibers are distributed by KrampeHarex®.

Type	Description	Name	Lenght (mm)	Diameter (mm)	Shape	Material-No.	Tensile strenghth (N/mm^2)
F1	micro wire fiber	DM 6/0,17	~9,0	0,15-0,22	round	1. 0620	min. 2100
F2	micro wire fiber	unknown	~18,0	~0,16	round	unknown	unknown
F3	glued fiber/hooked ends	DE 30/0,5 NG	~30,0	~0,5	round	1. 0313	~1250
F4	corrugated fiber	DW 50/1,0 N	~50,0	~1,0	round	1. 0313	~1100

Table 2: Properties of fibers F1-F4

Figure 3: Fibers F1-F4, placed on a magnet

3.1. Moulds

All moulds were made of pellucid sheet material withthe wall thickness of 4 mm (Figure 4). They were assembled using glue and machine screws made of non magnetic material. The inner dimensions of moulds S1 to S3 was 140 x 100 x 20mm, the proportions of the teeth were 10 x 10 x 20mm (S1), 20 x 20 x 20mm (S2) and 30 x 30 x 20mm (S3).The dimensions of S4 was 350mm (hight) x 150mm (outer diameter) x 15mm (wall thickness). Mould S5 had dimension of standardised mortar prisms, 160 x 40 x 40mm. Since the adhesive force of the magnets is antiproportional and the distance between the magnet and the fibers (Figure 6, left), the wall thickness of the moulds should be minimised as much as possible.

Figure 4: Moulds S1-S3 with different frontal connections, mould S4 for beams and mould S5 and S6 for investigations on thin walled pipes and plates (l. to r.)

3.1. Magnets

Two types of magnets were considered for the preliminary experiments: Permanent magnets and electromagnets. A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. An electromagnet is made from a coil of wire that acts as a magnet when an electric current passes through it. For the following reasons the choice for these tests was made for permanent magnets:

- A permanent magnet does not require a continuous supply of electrical energy to maintain its magnetic field, wich makes it easy to handle.
- The magnetic field of an electromagnet is partly covered by its construction, which limits the possible orientation of the magnets to the fibers .
- Permanent magnets, particularly modern neodymium magnets, are available of large choice of form and strength and individual magnets can be combined to bigger units creating specific magnetic fields.

Accordingly, permanent neodymium magnets (NdFeB) of different dimensions and polarity were chosen for the manipulators (Table 5). 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	block magnet	N42	40,0 x 20,0 x 5,0	axial, top and bottom	86.3
M2	block magnet	N45	20,0 x 20,0 x 3.0	axial, top and bottom	43.1
M3	block magnet	N40	50,0 x 15,0 x 5,0	axial, front surfaces	41.2
M4	bar magnet	N45	Ø 5,0 x 10,0	axial, front surfaces	9.3

Table 5: Properties of Magnets M1-M4

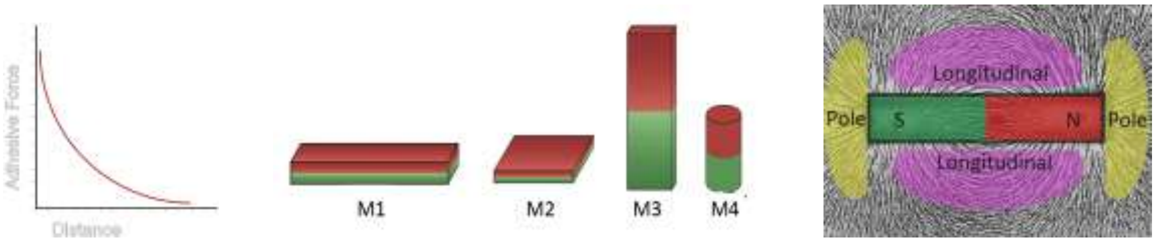

Figure 6: antiproportional relationship between adhesive force and distance (left), direction of magnetization of M1-M4 (middle), perpendicular field lines at poles and longitudinal ones in between (right)

4. Experimental research

The presented research covers the investigation of the ferromagnetic realignment applied on three crucial zones of structural elements: The frontal connection zone of thin shell element, the laminar region of shell structure elements and the tensile zone of beams.

4.1 The frontal connections (1D treatment)

For the first investigation, form-locking frontal connections between two segments of thin shells were magnetically treaded, including three different tooth-geometries S1, S2 and S3 (Figure 4).

As mentioned in the introduction, the aim of this series was to pull more fibers in the critical area of the teeth in order to increase resistance to bending moments, normal and shear forces. In particular the expected tensile and shear forces put the teeth at risk to be literally pulled. Previous tests on similar plates made from UHPRC showed that all cracks start at the roots of the teeth. Accordingly, the aim was to rearrange fibers perpendicularly to these zones known to be sensitive to cracking. Therefore all of the above described fibers and moulds were combined (12 combinations in total) and treaded exclusively with the pole-side of magnet M1 as a point source (1D treatment) (Figure 6, middle and right). The presented experiment should serve as an example of this first series of investigations. Therefore, mould S2 having teeth with a size of 20 x 20 x 20mm was chosen. These teeth represented simplified finger joints as they were developed in [1]. In the entire series the substitute was saturated with 2 Vol.-% content of the four types of fibers F1 to F4 (Figure 7) and then poured into the standing mould from the top.

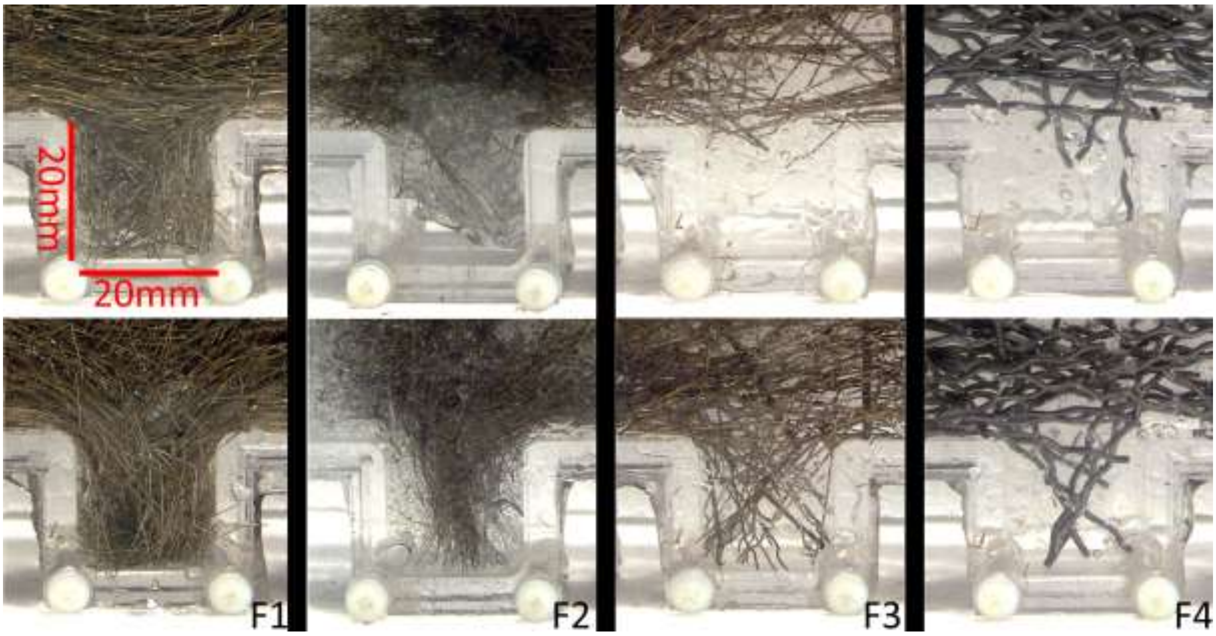

Figure 7: Tooth of mould S2 filled with fibers of type F1 to F4 (l. to r.), before (top) and after (bottom) the magnetic treatment

Observations

I) Before the magnetic treatment (Figure 7, top):

- The limited suitability of o the fibers F3 and F4 for the mould M2: the fibers did not flow into the teeth.
- The tendency that the fibers stretch over the teeth causing a dam formation.
- Balling of the fibers F2 and therefore interruption of the flow of the matrix.
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II) After the magnetic treatment (Figure 7, bottom):

- Using the pole-side of magnet M1, fibers could be pulled deeply into the teeth.
- Those fibers being longer than the teeth formed a cross that rested on the inner edges of the mould.
- Fibers F3 and F4 were long enough to extend into the plate as well as into the teeth.
- Only a small number of Fibers F4 could unhook and be pulled into the teeth.
- Fibers F1 and F2 were short enough to form felted strands that laid themselves on the inner edges of the mould.
- The balling of the fibers F2 was stretched and partly pulled into the tooth.

4.2 tensile zones (1D treatment)

In the second investigation the method was tested on a setup that aimed at the optimisation of the tensile zone of beams ans plates. The dimensions of the tested mould S4 was 40x40x160mm (Figure 4). There were two main aims for this expermient:

- To rearrange the fibers according to the expected direction of forces in the longitudinal direction of the mould
- To concentrate the rearranged fibers in the in the tension zone and accordingly lower arer of the mould

Due to its small dimensions and consequently high resolution, fibers F1 are able to show best the proceeding of the process. Therefore the experiment using fibers F1 is demonstrated here:

After filling mould S4 with the substitute mixed with 2 Vol.-% fiber content of fibers F1, a sequence of treatments was started (Figure 8, 1).: Therefore, 16 magnets of type M2 were assembled into a double-layered block of 2 x 4 magnets each layer. This block was slided under the bottom of the mould in longitudinal direction at a speed of approximately 0.2 m/s (Figure 8, 2). This sequence was repeated five times, until all fibers were concentrated on the bottom of the mold. Because of the strong field lines near the poles of M2, it was used to pull the fibers down. Some of the fibers remained standing perpendicular to the bottom of the mould (Figure 8, 2, left part). In a further step, the longitudinal field of magnet M3 was used to rearrange all concentrated fibers along the desired direction (Figure 8, 3a&b).

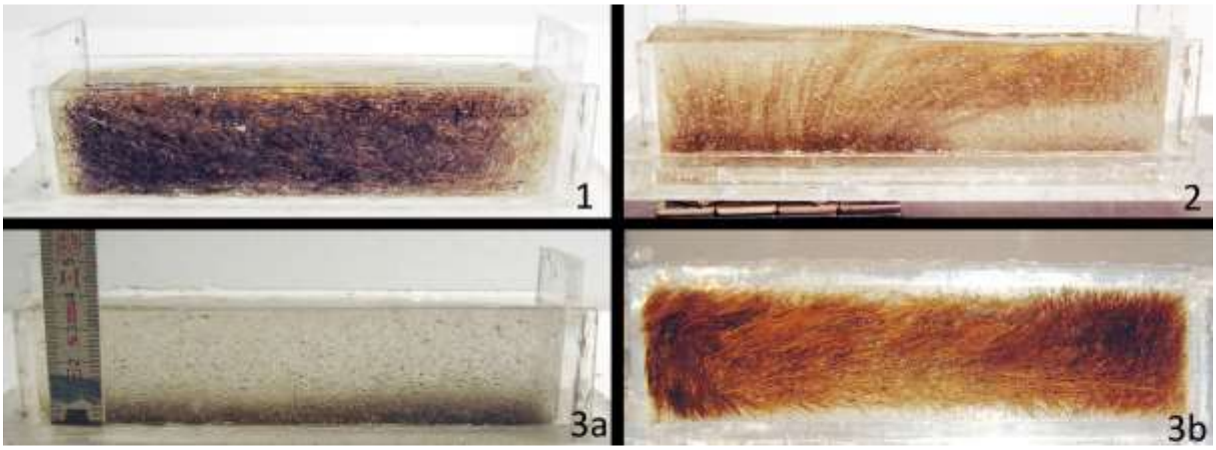

Figure 8: Mould S4 filled with fibers of type F1 before (1), during (2) and after the magnetic treatment (3a and 3b)

Observations

I) Before the magnetic treatment (Figure 8, 1):

- The fibers mixed with the substitute and poured into the mould don't show any regularity

II) During the magnetic treatment (Figure 8, 2):

- The block of magnets M2 pulled the fibers down to the bottom.
- As observed in 4.1, the pole-side of magnet M2 achieved a movement of the fibers perpendicular to the magnet.
- Using the longitudinal side of a magnet with poles at its front surfaces (e.g. M3, M4), fibers could be rearranged parallel to the magnet.

III) After the magnetic treatment (Figure 8, 3a&b):

- All fibers could be moved to the bottom of the mould.
- By the magnetic treatments, the fibers were concentrated as a longitudinal stand. This strand was pulled by the movement of the magnet M3 and gathered partly at both ends of the mould.
- Here, the former longitudinal orientation of the fibers was partly changed.

4.3 The laminar region of shell structure elements (2 D treatment)

The third series of experiments was concerned with the appliance of the method on flat and couved elements. Here, the laminar region of plate and shell structure elements was represented by mould S4 and S5 (Figure 4). These experiments were regarded as an extension of the former investigations due to the addition of a second dimension (2D treatment).

As illustrated in 4.2, it was possible to rearrange chaotically distributed fibers to continuous strands that could be aligned according to the estimated flow of forces. The further experiment documented in Figure 9 shows the attempt to cross two strands in a specific angle, as it might be beneficial for torsion reinforcement. Therefore, a cross-shaped pattern assembled of 20 magnets M2 was arranged on a flexible sheet of metal. This flexible stamp, wrapped around the cylindrical mould S5 (Figure 4), was used to emboss a pattern into the saturated matrix in order to gather fibers and to preprogram the path of the second sequence (Figure 9, image b): As described in chapter 4.2, the longitudinal field of magnets M3 and M4 was used to rearrange all concentrated fibers along the desired direction and to interfuse the strand at the area of their intersection.

Figure 9: Mould S5, shaping of interfusing strands

Representing a combination of the experiments shown in chapter 4.3 and 4.4, this attempt is an example of both point-sourced (1D) and linear (2D) treatment. Several sequences were executed to achieve a distribution of the fibers according to the flow of forces: The fibers, intending to create strong supports, were pulled deep into the teeth and, on the opposite side, far into the plate in order to create long and strong roots. These roots could be connected to each other along the contour line of the mould (Figure 10 b&c). Magnets M1 were used for the frontal connections, M3 and M4 for shaping the connections and roots.

Figure 10: Mould S6, combined treatment of the frontal connections and the laminar region

Observations

I) Before the magnetic treatment

- The fibers mixed with the substitute and poured into the mould show disadvantageous distribution (Figure 9 and 10, a).

II) During the magnetic treatment (Figure 8, 2):

- The embossed cross-shaped pattern of magnets M2 create separated islands of concentrated fibers (Figure 9, b).
- The entanglement of crossing strand is difficult to shape (Figure 9, c).
- Using the longitudinal side of a magnet with poles at its front surfaces (e.g. M3, M4), fibers can be rearranged parallel to the magnet.

III) After the magnetic treatment (Figure 8, 3a&b):

- All strand in the mould will stick to the side of treatment

5. Conclusion

The described experiments showed the following observations:

- The results of the above discused tests show repeatable 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 fibers in the tensile zones could be achieved by using sets of magnets: They were aligned due to their specific characteristics and the particular choice of the fibers.
- A following multi-stage treatment of different types and movement of the magnets led to an additional refinement of the treated zones.
- Using the effect of moving these sets of magnets on the outside surface of the moulds in a rotary way, the concentration of fibers affected by the magnets was increased drastically.

The following two parameters still need to be improved:

- The correlation between the magnetic field and the properties of the investigated fibers regarding geometry (proportion, size, weight, resistance to flow), material (mechanical and ferromagnetic properties, corrosion resistance), and processability (resistance to balling).
- The influence of the actual rheometric properties of UHPC on magnetic rearrangement of the fibers. Therefore, the previously used substitute will be refined in terms of comparability to
    a) the flow characteristic of the freshly cast UHPC,
    b) extension of its storage life and
    c) sufficient translucency for visual control of the process cycles.

Beyond this, the verification of the expected improvement in performance of construction elements made of UPFRC is of crucial importance. Comparative tensile stress tests of treaded and untreated specimens using different types of fibers and magnetic treatments showed very promising results, further ones are currently in preparation.

The CNC-based automation of magnetic rearrangement of steel fibers in UHPFRC for precast concrete components is the present objective of this research.

References

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

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

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