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Magnetic orientation of steel fibres in self-compacting concrete beams: Effect on failure behaviour

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ABSTRACT

The magnetic orientation of steel fibres in transparent silicone oil and in fresh, self-compacting concrete (SCC) beams is studied experimentally. The effect of the generated fibre locations and orientations on the failure response of the SCC beams is determined by means of three-point bend tests. A relatively small coil was designed for the magnetic orientation of single and multiple fibres in the transparent silicone oil. The time required for orienting a single fibre was measured for a range of magnetic fluxes, which showed to strongly decrease with increasing magnetic field strength. The presence of gravel on the fibre orientation behaviour was considered in order to mimic the influence by a concrete aggregate, indicating that the gravel does not prevent rotations and chain formations of fibres. A larger coil was developed for the magnetic orientation of fibres in freshly casted SCC beams. The energy absorption capacity of SCC beams subjected to three-point bending scales approximately proportionally with the number of “well-oriented fibres” bridging the catastrophic failure crack, which emphasizes the importance of adequately orienting steel fibres with the magnetic orientation technique.

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1. Introduction

Plain concrete is a brittle material with a relatively low tensile strength and deformation capacity, which requires the application of steel reinforcement in order to avoid substantial cracking and catastrophic failure under service conditions. The principle of reinforcing concrete by steel bars is over 100 years old, but even to this day the majority of newly built concrete structures uses this concept. Despite this enormous success, the application of reinforcement bars introduces limitations to the design of a concrete structure; indeed, the concrete itself can be poured in arbitrary forms, but the application of relatively long and stiff reinforcement bars constrains its flexibility in shape. The shape of concrete designs may be further limited by the expenses of temporary formwork used for *in-situ* cast structures. One way to overcome these restrictions is to use precast steel fibre reinforced concrete; steel fibres are easily deformable, occupy little space and therefore offer large freedom in the selection of the structural geometry. The use of fibre reinforcement further demands a relatively low physical labour effort from the manufacturing workers, thus improving their

health condition and efficiency during construction. Such advantages not only have a positive effect on the standard building practice; they are also of utmost importance for the successful development of modern building technologies based on 3D printing of concrete, and should support a practical implementation of such technologies in large-scale building and civil engineering projects in the near future.

The use of concrete as a matrix material in fibre composites puts special requirements to its compaction characteristics and workability. In order to minimally disturb the location and orientation of fibres within the fluidic, viscous matrix, a special type of concrete is required that obviates the use of vibration pokers in the placement and compaction procedure. Self-compacting concrete (SCC) is a relatively new type of concrete that meets these demands; during placement it naturally fills the complete formwork and achieves compaction by means of its own weight, even in the presence of heavy reinforcement [13]. Hardened SCC is characterised by a uniform material structure and high density, as a result of which it possesses a durability comparable to that of classically vibrated concrete. In its fluidic state it has a moderate viscosity, which is necessary for ensuring uniform suspension of the solid particles during transportation, placement (without external compaction), and in the final curing phase.

Similar to steel reinforcement bars, steel fibres start influencing

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the mechanical response after cracking in concrete is initiated. Under increased deformation the fibres start to debond, and eventually will break or will be pulled out of the concrete matrix. The amount of energy necessary for pull-out and breakage of fibres contributes to the effective energy absorption capacity of the fibre composite, and depends on the strength and shape of the fibres and the friction mobilised between the fibres and the matrix [3,1,9,15]. The contribution of the fibres to the overall energy absorption capacity reduces strongly if the fibres are pulled out under an angle that is more than 30 degrees off from the longitudinal fibre direction [3,1,16]. It is therefore highly desirable to optimize the energy absorption capacity by explicitly tuning the fibre orientation to the applied loading direction.

In the present communication, it is explored how randomly-oriented fibres in a viscous concrete matrix can be directed efficiently through the application of a magnetic field. In addition to a broad application in the standard building practice, this technique has great potential for being integrated in 3D printing technologies, as an electromagnetic coil can be relatively easily wound around the printing nozzle from which the viscous concrete is discharged. For a successful realization of this conceptual idea, however, more insight is needed into the basic mechanisms governing the magnetic fibre orientation process. Furthermore, the technical aspects that require improvement in order to practically implement this approach should be better identified. Hence, one of the main goals of the present research is to explore how the magnetic orientation of a relatively low volume percentage of steel fibres (0.5%) can increase the effective energy absorption capacity of concrete, considering that the brittleness of the plain concrete currently used in pilot 3D printing technologies induces severe limitations for a broad practical application in the short term.

The idea of aligning ferromagnetic fibres in concrete by means of a magnetic field goes back to the patent of Miller and Björklund [10]; where fibres were oriented in freshly casted concrete slabs by moving these through a rectangular coil. The method was successfully tested on relatively small samples, and later modified and patented by Svedberg [17] for the alignment of fibres in a broader range of applications, such as large slabs and pavements cast in-situ. Very recently, fresh mortar samples with randomly distributed fibres were placed in a spiral coil and subjected to a magnetic field in order to optimally orient the fibres for resisting fracture under bending loading conditions [11]. The bending experiments indeed demonstrated that for samples with well-oriented fibres the energy absorption capacity is larger than for randomly oriented fibres.

The present study focuses on the orientation of steel fibres in freshly casted, self-compacting concrete beams, by moving the beam at constant speed across a supporting rolling structure through an electromagnetic coil. The orientation of the fibres was registered by means of X-ray images that were made after the beams were hardened and subjected to a three-point bend test. This procedure allows for relating the energy absorption capacity and other failure characteristics measured under three-point bending to the location and orientation of fibres. The electromagnetic coil used in the fibre orientation tests was designed by applying a combined experimental-numerical procedure, with the numerical results computed by a Finite Element Method Magnetics (FEMM) model. A relatively small coil was developed for the magnetic orientation of single and multiple fibres in transparent silicone oil with flow characteristics comparable to freshly casted SCC. The time required for orienting a single fibre was measured for a range of magnetic fluxes. The presence of gravel on the fibre orientation behaviour was considered in order to mimic the influence of a concrete aggregate. The results and knowledge obtained from these tests were used to design a larger magnetic coil for the

effective orientation of steel fibres in SCC beams. The potential of this method for increasing the energy absorption capacity of concrete beams is demonstrated through the analysis of the failure response under three-point bending.

The organization of the paper is as follows. In Section 2 the design procedure of the magnetic coil is treated. Section 3 discusses the magnetics orientation of single and multiple steel fibres in transparent silicone oil. The orientation of steel fibres in SCC beams is treated in Section 4, together with the results from the three-point bend experiments. Finally, Section 5 summarizes the main results of the tests and provides recommendations for future research, in particular in relation to the 3D printing of concrete.

2. Design of electromagnetic coil by an experimental-numerical procedure

The design of an electromagnetic coil that can be used for orienting steel fibres in a fluidic matrix of low to moderate viscosity is considered in this section. After determining the size and magnetic strength of the coil, the homogeneity of the magnetic field within the coil is explored by comparing experimental observations against numerical results computed with a Finite Element Method Magnetics (FEMM) model.

2.1. General design parameters

For generating a uniform magnetic field within a specific volume of space, a “solenoid–type” electromagnet was developed by compactly winding a 2 mm thick polyesterimide enameled copper wire coated with a 0.112 mm thick polyamide-imide (AWG 12) around a hollow cylindrically-shaped coil housing made of brass. The diameter of the copper wire was chosen relatively small in order to warrant a flexible winding during the coil manufacturing process and limit the production of heat during operation. The heat production of the copper wire was further controlled by applying a water cooling system at the coil ends. The number of windings of the coil was estimated from the design strength of the magnetic flux density B through the coil; for an infinitely long solenoid, the magnetic strength, $B = |\mathbf{B}|$, in the axial direction follows the expression [14]

$$B = \mu_0 n I, \quad (1)$$

where $\mu_0 (=1.257 \times 10^{-6} \text{ kg m/C}^2)$ is the magnetic permeability *in vacuo*, n is the number of turns in the winding (measured per meter length in the axial direction), and I is the electric current through the copper wire. The design magnetic strength B used in Eq. (1) was estimated *a-priori* from trial experiments with an electrical horseshoe magnet, by measuring the field strength minimally required for rotating a single steel fibre of 60 mm length embedded in a Portland cement paste with a w/c ratio varying between 0.4 and 0.5. The measured field strength appeared to be equal to 0.3 T at the poles of the horseshoe magnet and 0.1 T in between the poles. A design strength of $B = 0.25 \text{ T}$ was determined from the average of these two values and accounting for a 25% overcapacity of the coil. Since the Portland cement slurry used in the trial experiments appeared to have a relatively high consistency, it may be reasonably expected that this magnetic strength is sufficiently large for orienting fibres in suspensions with low to moderate viscous flow properties.

In order to reach the design magnetic strength, the electromagnet must be connected to a (maximal) power supply of 25 A at 120 V, where, in accordance with Eq. (1), the number of turns n in the winding needs to be larger than 8000 (per meter length). Here, the length of the magnetic coil could be kept within acceptable

bounds by applying a multiple layer winding. Since such a coil geometry differs from an ideal, infinitely long, single-layer wound solenoid, the minimal value of $n = 8000$ calculated from Eq. (1) could only be used as a first estimate; the actual magnetic field and its homogeneity within the coil was confirmed experimentally by using a magnetometer test, and numerically by developing a detailed Finite Element Method Magnetics (FEMM) model using an open source code (<http://www.femm.info/wiki/HomePage>). A coil geometry with an inner diameter of 110 mm and a length of 129 mm was chosen, which, depending on the homogeneity of the magnetic field within the coil, should be sufficiently large for including rotating fibres with a length up to 60 mm. Combining the coil length with the minimally required number of turns of the winding computed with Eq. (1) leads to $8000 \times 0.129 = 1032$ turns across the coil. The actual number of turns across the coil length was taken about 40% higher than this minimal value, i.e., $n = 1440$, resulting in 24 layers of 60 turns.

2.2. FEMM model

The above geometrical characteristics of the coil, together with the material properties of the copper winding (among which an electrical conductivity of 58 MS/m) and the value of the electric current of 25 A, were used as input for an axisymmetric FEMM model. An irregular mesh was constructed with approximately 5000 linear triangular elements. The variational form of the field equations solved for by the FEMM method relates to a magnetostatic problem, which is governed by the following two (out of four) Maxwell equations [14]

$$\nabla \cdot \mathbf{B} = 0,$$

$$\nabla \times \mathbf{H} = \mathbf{J}, \quad (2)$$

where $\mathbf{B}$ is the magnetic flux density (as introduced above), $\mathbf{H}$ is the magnetic field intensity, $\mathbf{J}$ is the electric current density and ∇ is the gradient operator. The centered dot denotes the inner product between two vectors and the symbol “ $\times$ ” designates their cross product. In correspondence with Eq. (2), the jump conditions that the vectors $\mathbf{B}$ and $\mathbf{H}$ must satisfy across a current-free surface are

$$\mathbf{n} \cdot [\mathbf{B}] = 0,$$

$$\mathbf{n} \times [\mathbf{H}] = 0, \quad (3)$$

with [...] denoting a discontinuity across the surface and $\mathbf{n}$ being the unit normal to the surface. Inside a material, the $\mathbf{B}$ and $\mathbf{H}$ fields are related via the magnetization $\mathbf{M}$ of the material by means of the standard relation [14]

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) = \mu_0(1 + \chi_m)\mathbf{H}. \quad (4)$$

Here, χ_m is the magnetic susceptibility of the material, which quantifies the proportionality between the $\mathbf{M}$ and $\mathbf{H}$ fields, i.e.,

$$\mathbf{M} = \chi_m \mathbf{H}. \quad (5)$$

In the absence of matter, $\mathbf{M} = \mathbf{0}$, and Eq. (4) reduces to

$$\mathbf{B} = \mu_0 \mathbf{H}. \quad (6)$$

Through Eq. (4) the magnetostatic problem essentially becomes governed by one independent field variable, i.e., $\mathbf{B}$. Since the magnetic permeability of the coil materials (brass, copper) and the surrounding air are virtually equal to the magnetic permeability *in vacuo*, μ_0 , in the FEMM simulation the magnetic susceptibility in Eq.

(4) is prescribed to be zero, $\chi_m = 0$. Note that the combination of Eq. (2)₂ and (6) leads to Eq. (1) after integration with respect to the geometry of the solenoid, with the magnitude of the magnetic field intensity being equal to $H = nI$. In order to account for the “infinite free space” around the coil, the perimeter of the computational domain was modeled as an open boundary, using impedance values that accurately reflect the decaying magnetic field at increasing distance from the coil. The magnetic field $\mathbf{B}$ is assumed to vanish when the distance from the coil becomes infinitely large, which, from Eqs. (3) and (6), is reflected by requiring the components B_n and B_t , normal and tangential to the boundary, to be zero at infinity:

$$B_n = 0,$$

$$B_t = \frac{H_t}{\mu_0} = 0. \quad (7)$$

2.3. Numerical versus experimental results

Fig. 1 shows the field lines (curved black lines) and magnitude (in color) of the magnetic flux density $\mathbf{B}$ generated by the coil, as computed with the axisymmetric FEMM model. The symmetrical cross-section of the coil is indicated by two identical squares (thick black lines), with the square in between (dashed white lines) denoting an area of $90 \times 70 \text{ mm}^2$ in which the strength of $\mathbf{B}$ is approximately homogeneous. Observe that the magnetic strength within the homogeneous area indeed is relatively close to the design strength of 0.25 T, and that the size of the homogeneous area of $90 \times 70 \text{ mm}^2$ appears to be large enough to include freely rotating steel fibres up to a length of 60 mm. Furthermore, the size of the computational domain is sufficiently large for realizing that the normal and tangential components of $\mathbf{B}$ at the open boundaries along the domain perimeter already closely match those of a vanishing magnetic field at infinity, i.e., the flux lines hit the open boundary (almost) perpendicularly (which is in agreement with Eq. (7)₂) where the corresponding magnetic strength is close to zero (thus approaching Eq. (7)₁).

In Fig. 2 the strength of the magnetic flux density $\mathbf{B}$ computed within the $90 \times 70 \text{ mm}^2$ homogeneous area (sketched in Fig. 1 by the dashed white lines) is validated against experimental values obtained from magnetometer tests. The flux density is plotted versus the distance along the inner coil diameter at the center of the homogeneous area (Fig. 2a), and at its boundary located at a vertical distance of 35 mm from the center (Fig. 2b). The homogeneity of the magnetic flux density can be confirmed from the relatively small fluctuation along the coil diameter, as observed in both the numerical and experimental results. Furthermore, the numerical and experimental results generally are in good agreement; the maximal overestimation by the FEMM model remains limited to 10%, which occurs at the boundary of the homogeneous area, near the inner perimeter of the coil housing (represented by distances of 0 and 110 mm in Fig. 2b). Adjacent to the coil housing the experimental values for the magnetic strength are relatively close to the design strength of 0.25 T, especially at the center of the homogeneous area. Along the symmetry axis of the coil (represented by a distance of 55 mm) the experimental value is minimal at the boundaries of the homogeneous area, i.e., 0.212 T. This value is approximately 15% less than the design magnetic strength of 0.25 T, which was found acceptable. In summary, it may thus be concluded that the magnetic coil indeed is able to deliver the maximal design magnetic strength of 0.25 T, and generates an area of $90 \times 70 \text{ mm}^2$ with (a nearly) homogeneous magnetic field, which should be sufficient for encapsulating rotating fibres with a length up to 60 mm.

Fig. 1. Field lines (curved black lines) and strength (color) of the magnetic flux density B generated by a coil with a length of 129 mm and an inner diameter of 110 mm, as computed with an axisymmetric FEMM model. The symmetrical cross-section of the coil is indicated by the two identical squares (thick black lines), with the square in between (dashed white lines) denoting an area of $90 \times 70 \text{ mm}^2$ in which the strength of B is approximately homogeneous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Strength of magnetic flux density B along the coil diameter at two locations within the $90 \times 70 \text{ mm}^2$ homogeneous area (displayed in Fig. 1 by the dashed white lines); experimental result (black line) versus numerical FEMM result (grey line). a) Flux density evaluated at the center of the homogeneous area (indicated by the dashed red line in righthand inset). b) Flux density evaluated at the boundaries located at a vertical distance of 35 mm from the center (indicated by the dashed red lines in the righthand inset). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Magnetic orientation of fibres in a viscous silicone oil

The electromagnetic coil described in the previous section was used for examining the magnetic orientation of single and multiple steel fibres suspended in a viscous matrix. The viscous medium was

a transparent silicon oil (60000 CST), which enables a visual observation of fibre orientation effects during the magnetization process. The plastic flow properties of a fluidic, viscous medium subjected to simple shear may be described by the Bingham model [4]

$$\tau = \tau_0 + \mu\dot{\gamma}, \quad (8)$$

with τ the critical shear stress, τ_0 the yield value and μ the plastic viscosity of the medium. The values for the plastic viscosity and the yield stress of the silicone oil are $\mu = 60 \text{ Pa}\cdot\text{s}$ and $\tau_0 = 0 \text{ Pa}$, respectively. These values are similar to the recommended values for low-viscosity, Self-Compacting Concrete (SCC), where the yield value should range between 40 and 60 Pa at a low plastic viscosity of $10 \text{ Pa}\cdot\text{s}$, with a linear decrease to a range between 0 and 20 Pa at a higher plastic viscosity of $50 \text{ Pa}\cdot\text{s}$ [12]. The similarity in rheological characteristics allows for combining the results of the present test series with those from the magnetic orientation of steel fibres suspended in SCC samples, see Section 4.

3.1. Orientation of a single fibre

In the magnetic orientation tests on single fibres 5 different high-strength steel fibres were analysed, see Fig. 3, of which the characteristics are specified in Table 1. Apart from iron and carbon, the steel fibres were composed of small percentages (<0.5 wt %) of additional elements, such as silicon, manganese, phosphor and sulfur.

An individual fibre was positioned in a transparent bowl filled with silicone oil, whereby its initial axial direction was oriented perpendicular to the magnetic field applied in the longitudinal direction of the coil. The transparent bowl was located at the centre of the coil, and the time it takes to orient the fibre in the direction of the magnetic field was measured for 5 different magnetic field strengths, namely 0.0046 T (0.5 A), 0.0092 T (1.0 A), 0.0137 T (1.5 A), 0.0183 T (2.0 A) and 0.0229 T (2.5 A), where the value between parentheses reflects the corresponding electric current through the coil. The magnetic flux density represents the average value generated in the $90 \times 70 \text{ mm}^2$ homogeneous area displayed in Fig. 1 (by the white dashed lines). Note that the above values for the magnetic strength are substantially smaller than the design magnetic strength of 0.25 T derived from the rotation of a single fibre in

Fig. 3. Overview of five different high-strength steel fibres used in the magnetic orientation tests. The fibre types are (from top to bottom): Dramix 3D, Dramix 4D, Dramix 5D, MPZ, MPZ HT, see Table 1 for the fibre characteristics.

Table 1

Geometrical and material characteristics of 5 different high-strength steel fibres used in the magnetic orientation tests in silicone oil.

Type	Length [mm]	Diameter [mm]	Tensile strength [N/mm ²]
Dramix 3D	60	0.75	1225
Dramix 4D	60	0.90	1500
Dramix 5D	60	0.90	2300
MPZ	50	0.8	>1100
MPZ HT	50	1.0	>1400

a Portland cement paste, see Section 2.1, which likely is caused by the considerably lower viscosity of the silicone oil.

The measurement results are depicted in Fig. 4, indicating that the time it takes to adequately rotate the fibre decreases on average by a factor of 10 (from 150 s to 15 s) when the flux density increases by a factor of 5 (from 0.0046 T to 0.0229 T). The final rotation of all fibres was close to 90°; in specific, relatively small offsets of 6 and 12° were observed for the Dramix fibres and MPZ fibres, respectively. This can be explained from the fact that the fibre ends are hooked and break its axisymmetry, thereby inducing a small misalignment between the longitudinal fibre axis and the principal axis of minimal mass moment of inertia. The noticeable difference in rotation times measured for the Dramix 3D and 4D fibres at a flux density of 0.0092 T is somewhat unexpected, considering that the geometrical properties of these two fibres are identical, see Table 1. It is concluded that this difference may be due to small measurement inaccuracies, which probably are also the cause for the relatively high rotation time of the MPZ fibre at a flux density of 0.0137 T. Although the magnetic strength minimally required for the rotation of the MPZ fibres is smaller than that for the Dramix fibres, all 5 curves show a similar trend, which can be approximated by a power function

$$t_{\text{rot}} = \alpha B^{-\gamma}. \quad (9)$$

Here, t_{rot} is the rotation time (in seconds), B is the strength of the magnetic flux (in Tesla), and α (in seconds·Tesla $^{\gamma}$) and γ (dimensionless) are calibration parameters. The accuracy of the above power function is illustrated in Table 2 by listing the values of the calibration parameters determined by a least-squares fit of the experimental data, together with the corresponding R^2 -values. The least-squares fit of Eq. (9) to the average experimental values for the 5 fibres is also provided. It can be observed that all R^2 -values are

Fig. 4. Time (in seconds) required for a 90° rotation of a fibre suspended in transparent silicone oil versus the corresponding magnetic flux density (in Tesla). The characteristics of the 5 fibres tested are listed in Table 1. The least-squares fit of Eq. (9) to the average values of the data measured for the 5 fibres is also plotted.

Table 2Calibrated values of α and γ appearing in Eq. (9).

Type	α [seconds $\cdot$ Tesla $^{\gamma}$]	γ [–]	R ² -value
MPZ	0.188	1.262	0.932
MPZ HT	0.012	1.802	0.964
Dramix 3D	0.145	1.274	0.980
Dramix 4D	0.030	1.673	0.974
Dramix 5D	0.019	1.803	0.971
Average fit	0.087	1.408	0.979

rather close to unity, indicating an accurate fit.

3.2. Orientation of multiple fibres

As a next step, the magnetic orientation capacity of multiple fibres suspended within transparent silicone oil was studied, with and without the placement of 8–10 mm gravel stones. The gravel is supposed to mimic the blocking effect by an aggregate typically present in a concrete composition. In each test 20 to 25 fibres were applied, for which the 60 mm fibres used in the single fibre test described in Section 3.1 were reduced in length by a factor of 4–6 in order to allow for mutual fibre interactions and interactions with the gravel. The transparent bowl containing the oil, the fibres and the (optional) gravel was placed in the center of the coil. The fibres and gravel stones were distributed relatively uniformly across the bowl area, with their initial orientation chosen arbitrary. The strength of the magnetic flux density of the coil was taken as 0.046 T, and was generated with an electric current of 5 A. Preliminary tests indicated that this magnetic strength is sufficient for orienting all fibres within a period of 30 s along the magnetic field lines in the longitudinal direction of the coil [20].

The initial and final fibre locations and orientations are shown in Fig. 5 for the sample *without gravel stones* and in Fig. 6 for the sample *with gravel stones*. During the application of the magnetic field for a period of 30 s the individual fibres started to rotate in order to become aligned with the longitudinal field lines. In

addition, individual fibres moved towards each other, leading to the chain formations depicted in Figs. 5b and 6b. The clustering of fibres into four or five different chains is caused by their dipole behavior induced by the applied magnetic field, where oppositely charged fibre ends attract each other and equally charged fibre ends repel each other. A similar interactive behavior has been observed for electro-magnetic particles with sizes ranging between 1 μ m and 1 mm, which appear in various mechanisms and devices, such as electrostatic copiers and fluidized beds [8]. The amount of fibre overlap following from the dipole-dipole interactions strongly depends on the initial distance between fibre ends; for the MPZ HT fibres an overview of the relative overlaps observed in the tests is presented in Fig. 7, with x being the initial distance between two fibre ends and L being the fibre length. This figure shows that a shorter distance between fibre ends leads to more fibre overlap. Notice from Fig. 6b that the presence of gravel stones does not arrest the combined rotation and chain formation of fibres; the fibres tend to follow the path of least resistance in order to become aligned with the magnetic field lines, whereby gravel stones are only slightly rotated and/or displaced during contact with fibres. Obviously, for larger fibre lengths the obstructive behavior by the gravel may be stronger, which makes the fibre length versus the size and distribution of gravel an important design parameter in the fibre orientation process.

Although not illustrated here, it was observed that magnetic flux densities higher than 0.046 T may lead to substantial displacements of gravel stones during contact with fibres. This effect obviously is undesirable in concrete, as it results in an inhomogeneous aggregate distribution with areas of relatively low material strength. For the same reason, a strongly localized clustering of fibres into longitudinal chains should be avoided, which, for the orientation of steel fibres in concrete, can be accomplished by carefully monitoring the magnetic field strength to the viscosity and yield stress of the fresh concrete. The magnetic orientation of fibres in self-compacting concrete is addressed in more detail in the subsequent section.

Fig. 5. Multiple fibres suspended in silicone oil. a) Initial configuration with the fibres distributed uniformly and oriented in arbitrary directions. b) Final configuration after the application of a 0.046 T magnetic field for a period of 30 s.

Fig. 6. Multiple fibres and gravel stones suspended in silicone oil. a) Initial configuration with the fibres and gravel stones distributed uniformly and oriented in arbitrary directions. b) Final configuration after the application of a 0.046 T magnetic field for a period of 30 s.

Fig. 7. Four different types of fibre overlap resulting from dipole-dipole interactions of steel fibres, expressed in terms of the fibre length L and the initial distance x between fibre ends.

4. Magnetic orientation of fibres in beams of self-compacting concrete

The magnetic orientation tests of steel fibres in beams made of self-compacting concrete (SCC) are discussed in this section. The steel fibres were manually placed in the SCC by constructing the beam layered-wise, after which a magnetic field was applied to rotate the fibres in the longitudinal direction of the beam. Subsequently, the SCC beams were hardened for a period of 28 days in order to perform a three-point bend test, see Fig. 8. In this test the SCC beams were placed on simple supports and loaded in a displacement-controlled fashion by a vertical force positioned at the beam centre, until catastrophic failure was reached. From the experimental response the Young's modulus, fracture strength and energy absorption capacity were determined. Subsequently, the relative fibre rotations induced by the magnetic field were visualized using X-ray photography. With this procedure it can be studied how the fibre rotations and locations relate to the failure characteristics observed under three-point bending conditions.

4.1. Preparation of beam specimens

The composition of the SCC used for constructing the beams was roughly based on a mixture described on page 38 of [6]; with some adjustments made in order to improve the workability of the mixture. The composition of the mixture is presented in Table 3. First, the sand and cement were mixed adequately and combined with 80% of the total amount of water. The superplasticisers were

then added together with 20% of the remaining water until a homogeneous substance was obtained.

The rheological properties μ (plastic viscosity) and τ_0 (yield stress) of fresh SCC, as represented in Eq. (8), were obtained from preliminary BML viscometer tests by subjecting the measured data to a linear regression and substituting the result in the Reiner-Rivling equations [18,19]. Two samples of SCC were examined in three separate viscometer tests performed at 20 min time-intervals. The spread in the measured viscous properties appeared to be significant: the plastic viscosity μ ranged between $26.6 \text{ Pa} \cdot \text{s}$ and $39.0 \text{ Pa} \cdot \text{s}$, and the yield stress varied between $\tau_0 = 25.1 \text{ Pa}$ and 51.9 Pa [20]. Here, the small values correspond to the first test and the larger values to the last test, thus characterizing the time development of the rheological properties of fresh SCC shortly after the manufacturing process. Note that on average the viscosity of the SCC appears to be somewhat lower than the viscosity of the silicone oil used in the magnetic experiments described in Section 3, while the yield stress is somewhat higher.

Subsequently, the variation in rheological properties within one batch of 70 L of fresh SCC was explored by performing BML viscometer tests on samples taken at 3 different batch locations. For each of the samples the time evolution of the torque experienced by the mixer is shown in Fig. 9. The magnitude of the torque initially distinguishes four subsequent stages, in correspondence with a stepwise increase of the number of revolutions per minute (rpm) of the mixer from 20 to 40, 60 and finally to 80. At 80 rpm the steady-state value of the torque is reached after about 5 min, and for the three samples equals 290 Nmm, 297 Nmm and 335 Nmm. The difference between the smallest and largest value of the torque is approximately 15%, which, in accordance with the Bingham

Table 3
Mixture composition of SCC.

Component	Weight [kg/m ³]
Cement: CEM III 42.5 N	983
Water	269
Sand (0–4 mm)	1042
Superplasticiser Glenium 27	2.24
Superplasticiser Glenium 51	3.93
Water/cement ratio	0.27
Water/binder ratio	—

Fig. 9. Time evolution of the torque experienced by the mixer in viscometer tests on three different SCC samples taken from one batch. The magnitude of the torque initially distinguishes four subsequent stages, in correspondence with a stepwise increase of the number of revolutions per minute (rpm) of the mixer from 20 to 40, 60 and finally to 80. At 80 rpm the steady-state value of the torque is reached after about 5 min.

Fig. 8. SCC beam subjected to a three-point bend test.

Fig. 10. Fibre volume percentage (top) and fibre locations (bottom) in a $400 \times 100 \times 100 \text{ mm}^3$ beam constructed of 10 consecutive layers of SCC.

model given by Eq. (8), provides a rough indication of the percentual variation in rheological properties that can be expected within one and the same batch of SCC.

Beams of $l \times b \times h = 400 \times 100 \times 100 \text{ mm}^3$ were made by consecutively putting 10 layers of concrete on top of each other, where in between each layer 17 fibres (type MPZ HT, see Table 1 for its characteristics) were distributed uniformly across the middle third of the specimen, see Fig. 10, with their orientation taken in the width direction of the beam. The amount of steel fibres corresponds to a local volume percentage of 0.5%. When passing the beams through the magnetic coil, the fibres thus preferentially should rotate by 90° , such that they become oriented in the longitudinal direction of the beam and are able to provide a maximal contribution to the failure resistance under three-point bending.

4.2. Magnetic coil

The magnetic coil described in Section 2 is too small to encapsulate the concrete beams, so this coil was scaled up by using a larger brass coil housing with a length of 300 mm and an inner diameter of 310 mm. A 2.36 mm thick copper wire coated with a 0.112 mm thick polyamide-imide (AWG 11) was wound in 16 layers of 121 turns across the length of the coil. By restricting the electric current to be maximally 13 A, the heat produced by the coil during operation could be kept limited, such that the application of a water cooling system was not necessary. As for the small coil described in Section 2, for the large coil the generated magnetic field was measured and compared to the field computed with an axisymmetric FEMM model. The FEMM model was built with approximately 15000 linear triangular elements using an irregular mesh. Fig. 11 shows the field lines (curved blue lines) and magnitude (in color) of the flux density $\mathbf{B}$ generated by the coil at an electric current of 13 A. It can be observed that the magnetic field is approximately homogeneous within the central area of $300 \times 150 \text{ mm}^2$ (indicated by the white dashed lines).

In Fig. 12 the computed and measured flux densities along the coil diameter are compared in more detail at the center of the coil (Fig. 12a) and at the boundary of the central homogeneous area located at a vertical distance of 75 mm from the center (Fig. 12b). The average experimental flux density at the centre of the coil is about 0.08 T, while at the boundary of the central homogeneous area it is slightly lower. More specifically, the maximal percentage difference in flux density along the coil diameter is about 11%, both for the numerical and experimental result, thus confirming the appearance of an approximately homogeneous magnetic field. It is concluded that the correspondence between the experimental and numerical values generally is good.

4.3. Magnetic orientation of steel fibres

In the fibre orientation tests on the SCC beams the strength of the magnetic flux density within the coil was set at a value of 0.02 T, which could be accomplished through a power supply of 3.5 A and 26 V. Preliminary tests indicated that this value of the magnetic

Fig. 11. Field lines (curved blue lines) and strength (color) of the magnetic flux density $\mathbf{B}$ generated by a coil with a length of 300 mm and an inner diameter of 310 mm, as computed with an axisymmetric FEMM model. The symmetrical cross-section of the coil is indicated by the two identical squares (thick black lines), with the square in between (dashed white lines) denoting an area of $300 \times 150 \text{ mm}^2$ in which the strength of $\mathbf{B}$ is approximately homogeneous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Strength of magnetic flux density B along the coil diameter at two different locations within the $300 \times 150 \text{ mm}^2$ homogeneous area (displayed in Fig. 11 by the dashed white lines); experimental result (black line) versus numerical FEMM result (grey line). a) Flux density evaluated at the center of the homogeneous area (indicated by the dashed red line in righthand inset). b) Flux density evaluated at the boundaries located at a vertical distance of 75 mm from the center (indicated by the dashed red lines in the righthand inset). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strength allows for adequately orienting most of the magnetic fibres within a period of 30 s, thereby limiting their clustering [20]. Note that this combination of rotation time and magnetic field strength is in good agreement with the measurement result for single fibres suspended in transparent silicone oil, see Fig. 4. Three freshly cast concrete beams were subsequently pulled through the magnetic coil at a constant velocity of 5 mm/s, exposing each of the beams to the magnetic field for a period of 80 s. It is emphasized that the main purpose of these tests is to explore the capability of the magnetic field to adequately orient steel fibres in fresh concrete, and to examine if the resulting degree of fibre orientation consistently relates to the failure characteristics of hardened concrete, in particular to the energy absorption capacity. Further in this communication it will indeed turn out that these research questions can be answered by performing only three tests, whereby it is reasonably accepted that for this number of tests the experimental results may not be formally interpreted as “statistically representative”. In order to guide the beam smoothly through the coil, a supporting rolling structure made of wooden cylinders was constructed, across which the concrete beam was pulled by connecting its mold to a rope that was wound up steadily along a winch, see Fig. 13. The maximal error in the guiding velocity appeared to be about 10% when the rope was manually wound up along the winch. Since the magnetic permeability of wood is virtually equal to that of air, the supporting structure does not influence the magnetic field generated by the coil.

After the reinforced beams were subjected to the magnetic fibre orientation process, they were hardened for a period of 28 days at a relative humidity of 100% and a temperature of 20°C , in order to determine their failure behaviour from displacement-controlled,

Fig. 13. Test set-up for the magnetic orientation of steel fibres embedded in a concrete beam. The magnetic coil is connected to a supporting rolling structure made of wooden cylinders, across which the concrete beam is pulled by connecting its mold to a rope that is wound up steadily along a winch.

three-point bend tests. The loading apparatus used is a Schenck RM100 (Schenck, Germany), equipped with a 100 kN load cell. A 380 mm support span and a loading rate of 0.2 mm/min were utilized. The 28-days compressive strength of the concrete composition specified in Table 3 was determined by using three 150 mm cylindrical test specimens in accordance with NEN-EN 13791. The characteristic compressive strength equals 54 MPa, which classifies this concrete as C60/75. When the three-point bend tests were finished, the beams were cut with a diamond saw into 9 equal-sized, rectangular slices of $l \times b \times h = 133 \times 33 \times 33 \text{ mm}^3$, see Fig. 14. Each of the slices was subjected to X-ray imaging in order to visualize the effect of the magnetic field on the

Fig. 14. Character denotation of the 9 equal-sized, rectangular slices in which the concrete beam was cut for creating X-ray images (after loading in three-point bending).

final location and orientation of the steel fibres. With this procedure, the relation between the fibre orientations and the failure characteristics of the beam under three-point bending could be explored.

In Figs. 15–17 the fibre orientations in three different concrete beams - numbered as #1, #2 and #3, respectively - are shown after exposure to a magnetic field of 0.02 T. Observe that for beam #1 the majority of steel fibres experienced a 90° rotation with respect to their original orientation, which was in the width direction of the beam, see Fig. 10. As for the steel fibres tested in the silicone oil, dipole-dipole interactions resulted in individual fibres moving

towards each other, leading to fibre overlap and fibre clustering. For beam #3 the average fibre rotation was somewhat less than for beam #1, while for beam #2 most of the fibres remained relatively close to their original orientation. In addition, for beams #1 and #3 it can be noticed that most fibres originally present at the top part of the beam moved to the middle and bottom parts as a result of gravitational effects. Conversely, for beam #2 most fibres originally located at the top part of the beam remained there after applying the magnetic field. This effect, together with the relatively small fibre rotations, suggests that the viscous strength of the SCC in beam #2 was significantly higher than in beams #1 and #3. As demonstrated by the results of the BML viscometer tests presented in Section 4.1, such differences between specimens indeed are plausible, considering the strong variation in time of the rheological properties of fresh SCC measured shortly after the manufacturing process was finished, and their spatial variability within one and the same batch of concrete.

The motion of a steel fibre within the viscous concrete is essentially driven by contributions from the magnetic interaction force and the hydrodynamic drag force [5]. The first contribution is set by the strength of the magnetic field, while the second contribution is determined by the viscosity of the fresh concrete. The above experiments show that the strong time and spatial variations of the rheological properties of fresh SCC samples make it difficult

Fig. 15. Fibre locations and orientations in concrete beam #1 after the application of a magnetic field of 0.02 T. All fibres were initially oriented in the width direction of the beam, see Fig. 10. The beam was cut into 9 equal-sized, rectangular slices, where each slice is indicated by two characters, as designated in the overview in Fig. 14. The first character indicates the front (A), middle (B) or back (C) part of the beam, and the second character designates the top (1), middle (2) or bottom (3) part of the beam. The failure crack at the centre of the beam resulted from the loading applied in a three-point bend test.

Fig. 16. Fibre orientation in concrete beam #2 after the application of a magnetic field of 0.02 T.

to determine the appropriate magnetic field strength for achieving the required fibre orientations at all locations within the beam. Hence, more research is necessary on finding effective solutions for a better control of the viscous properties of fresh SCC in time and within a batch.

4.4. Effect of fibre orientation on failure response under three-point bending

For the three unnotched fibre-reinforced beams depicted in Figs. 15–17 the failure responses under three-point bending are shown in Fig. 18, by plotting the vertical load applied at the centre of the beam versus the load point deflection. The measurement of the load point deflection has been corrected for the deformation of the test set-up. The initial part of the responses, illustrated in detail in the inset of Fig. 18, represents the elastic behaviour of the SCC concrete beam. By applying Euler-Bernoulli beam theory,¹ the Young's modulus derived from these branches is $E = 36$ GPa. The peak loads for the three specimens show some variations, and are equal to 9.38 kN, 8.65 kN and 10.72 kN for beams #1, #2 and #3, respectively. The corresponding bending tensile strengths obtained

with elementary beam theory are 5.3 MPa, 4.9 MPa and 6.1 MPa, respectively, see also Table 4. Additional three-point bend tests on *unreinforced beams* (not presented here) demonstrated that for these specimens the Young's modulus and bending tensile strength had similar values as for the fibre-reinforced beams, from which it may be concluded that the addition of fibres has a negligible effect on the stiffness and maximal strength of the beam. This is not surprising, considering the relatively low volume percentage of steel fibres applied, i.e., 0.5% across the middle third of the beam, see Fig. 10. A similar result was found in the experimental study of [11]. The bending tensile strengths mentioned above fall within the range of values of 3–7 MPa typically measured for conventional and high strength concretes made with hydraulic binders [2]. After reaching the peak strength, the applied force shows a sudden drop, which characterizes the initiation of a macroscopic failure crack near the centre of the beam. The crack opening activates crack bridging by steel fibres, by which the failure crack gets arrested and the abrupt drop in force remains limited. Subsequently, the force decreases gradually with increasing deformation, as characterized by a relatively smooth softening branch. At the end of the softening branch the failure crack has run across the complete specimen height, whereby the fibres initially bridging the crack have broken or have been pulled out of the concrete matrix. Observe from Fig. 18 that the ultimate displacements at which the beams failed equal 8.3 mm, 4.1 mm and 7.2 mm for beams #1, #2 and #3, respectively. At these deformations the corresponding load applied abruptly drops to zero; this brittle behaviour is caused by the lack of

¹ Shear deformations are ignored here for reasons of simplicity; although this is not fully correct, it may be assumed that for a beam length-to-height ratio of 4:1 the shear contribution to the overall deformation behaviour under three-point bending is relatively small.

Fig. 17. Fibre orientation in concrete beam #3 after the application of a magnetic field of 0.02 T.

Fig. 18. Failure responses of fibre-reinforced concrete beams under three-point bending; the vertical load applied at the centre of the beam is plotted versus the load point deflection. The inset shows in detail the initial elastic response and the maximal load of the three beams.

presence of fibres in the top part of the beam (due to gravitational effects), see Figs. 15 and 17, or limited crack bridging (due to an

insufficient orientation of fibres), see Fig. 16.

The failure behaviour depicted in Fig. 18 is considerably different

Table 4

Maximum bending tensile strength, energy absorption capacity, number of well-oriented crack-bridging fibres and energy absorption capacity per well-oriented crack-bridging fibre for the three specimens tested.

Specimen number	Bending tensile strength [N/mm ²]	Energy absorption capacity G_f [N/mm ¹]	Number of well-oriented crack-bridging fibres	Energy absorption capacity per well-oriented crack-bridging fibre [N/mm ¹]
#1	5.3	4.8	21	0.23
#2	4.9	1.1	5	0.22
#3	6.1	3.5	12	0.29

from that of the (brittle) unreinforced beams tested, where the applied load *immediately dropped to zero* after reaching the peak strength. Accordingly, the gain in ductility obtained with fibre reinforcement is substantial, and can be quantified by means of the energy absorption capacity of the specimen. The total area U under the force-displacement curve represents the energy required for breaking the specimen; when dividing this energy by the uncracked cross-sectional area A of the beam, a measure for the energy absorption capacity G_f is obtained [7]. The values obtained for the energy absorption capacity G_f of the three specimens are listed Table 4. These values can be associated to the level of fibre rotation depicted in Figs. 15–17, by counting the number of “well-oriented fibres” bridging the catastrophic failure crack, i.e., the fibres with rotation angles *less than 30 degrees* off from the required rotation of 90°. This maximal offset in final fibre orientation is in correspondence with the experimental observations reported in [1,3,16], which show that the contribution of the fibres to the overall energy absorption capacity reduces strongly if the fibres are pulled out under an angle that is more than 30 degrees off from the longitudinal fibre direction. In the current tests the maximal and minimal fracture energies indeed correspond to beams #1 (highest fibre rotation, with 21 well-oriented crack-bridging fibres) and #2 (lowest fibre rotation, with only 5 well-oriented crack-bridging fibres), respectively, and the intermediate energy absorption capacity to beam #3 (intermediate fibre rotation, with 12 well-oriented crack-bridging fibres). The relative difference in energy absorption capacity thus is maximal for specimens #1 and #2, namely a factor of 4.5, in accordance with the presence of 4.2 times more well-oriented fibres across the failure crack. For beams #1 and #3 the relative difference in energy absorption capacity is 1.4, in correspondence with the presence of 1.7 times more well-oriented fibres across the failure crack. It can thus be concluded that the energy absorption capacity scales approximately *proportionally* with the number of well-oriented fibres bridging the catastrophic failure crack. This can also be concluded from the similarity in the values of the energy absorption capacity per well-oriented, crack-bridging fibre, see Table 4, which for the three beams tested all lie between 0.2 and 0.3 N/mm¹.

5. Conclusions

The study presented in this communication has provided a number of novel insights and conclusions on the magnetic orientation of steel fibres in SCC beams, which are summarized below.

- Under the application of a magnetic field the orientations of steel fibres may vary substantially per specimen, see Figs. 15–17. This is due to the strong time variations of the viscous parameters of fresh SCC measured shortly after finishing the manufacturing process, and their spatial variability within one and the same batch of concrete.
- The dipole-dipole interactions between steel fibres can result in individual fibres moving towards each other, leading to fibre overlap and fibre clustering, see Figs. 5b and 6b (silicon oil) and 15 (SCC). The extent to which this occurs should be

kept limited, and depends on the strength of the magnetic field in relation to the viscosity of the fluidic matrix.

- The time required for rotating a steel fibre by a specific angle strongly decreases with increasing strength of the magnetic field, and can be well approximated by a power function, see Eq. (9) and Fig. 4.
- The presence of gravel stones in the fluidic matrix does not arrest the combined rotation and chain formation of fibres of moderate to short length; the fibres tend to follow the path of least resistance in order to become aligned with the magnetic field lines, whereby gravel stones are only slightly rotated and/or displaced during contact with fibres, see Fig. 6b. The influence on this mechanism by the fibre length and distribution versus the gravel size and distribution is a topic for further research. In addition, preliminary experiments have shown that at relatively high magnetic flux densities gravel stones may undergo substantial displacements during contact with fibres. This effect obviously is undesirable for concrete, as it results in a relatively inhomogeneous aggregate distribution with areas of low material strength.
- In correspondence with the above observations, the motion of a steel fibre within viscous concrete is essentially determined by contributions from the magnetic interaction force and the hydrodynamic drag force. The first contribution is set by the strength of the magnetic field, while the second contribution is determined by the concrete viscosity. The experiments discussed in this communication show that the strong time and spatial variations of the viscous properties of fresh SCC make it a true challenge to determine the appropriate magnetic field strength for achieving adequate fibre orientations and limited fibre clustering under all circumstances. Hence, future research should focus on finding effective solutions for a better control of the viscous properties of fresh SCC in time and within a batch.
- The energy absorption capacity of SCC beams subjected to three-point bending scales approximately *proportionally* with the number of well-oriented fibres bridging the catastrophic failure crack, see Figs. 15–18 and Table 4. This emphasizes the importance of adequately orienting steel fibres with the magnetic orientation technique. The effect of the steel fibres on the bending tensile strength and the Young's modulus of SCC appears to be negligible, due to the relatively low volume fraction of fibres used in the current beam specimens.
- The magnetic orientation technique seems to be a useful and promising method for the alignment of steel fibres in SCC structures made under factory conditions and structures manufactured with 3D printing technology. Nonetheless, the integration of the magnetic orientation technique within a 3D concrete printer still asks for various technical issues and challenges to be solved. Illustrative examples that can be mentioned here are: preserving the uniformity in fibre distribution during the printing process, establishing the optimal location at which the fibres should enter the printing

facility, determining the appropriate magnetic field strength for adequately orienting the fibres during the printing of a low slump, highly thixotropic concrete, controlling the influence by the velocity of the discharged concrete on the fibre orientation, monitoring the fibre orientations during the printing process, etc. Additionally, it is interesting to explore the combination of using relatively large magnetic fibres for increasing the effective energy absorption capacity of printed concrete with smaller, randomly-oriented (non-magnetic) polymer fibres for increasing the tensile strength. These and other topics for future research are part of the authors' current research portfolio on 3D printing of concrete (see <https://www.tue.nl/3Dconcreteprinting> for more information), which strongly aims at the practical implementation of this promising technique in the civil engineering and building practices in the near future.

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