TESTING AND SIMULATION OF FIBRE ORIENTATION IN REINFORCED WALLS CAST WITH SFRSCC

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ABSTRACT

The potential of using steel fibres in load-bearing structures is still relatively unknown – in particular in connection with the application of self-compacting concrete, resulting in Steel Fibre Reinforced Self Compacting Concrete (SFRSCC). The structural performance of SFRC is strongly dependent on the fibre orientation and distribution and this holds true in particular for SFRSCC where the flow of the fresh material can cause extreme fibre orientation, which can be viewed as both a weakness and strength of the material.

Development of numerical tools to predict the flow of SFRSCC is important in order to understand the nature of fibre orientation and to benefit from fibre orientation in structural design. This paper presents a study on fibre orientation of SFRSCC in reinforced walls. A relatively large wall trial casting was carried out prior to the construction of an underpass bridge for a new city bypass. A small part of this wall was simulated using a newly developed numerical tool to simulate the flow of SFRSCC. Simulated and measured fibre orientation in three directions have been compared in terms of fibre counts.

Keywords: SFRSCC; Steel Fibres; Simulation; Wall; Casting; Rheology

INTRODUCTION

Combining steel fibres with traditional concrete – resulting in Steel Fibre Reinforced Concrete (SFRC) – has been known since the sixties and the structural use of SFRC has been known and applied for the past 30 years. However, there are still challenges to overcome in order to design steel fibre reinforced concrete structures in a more precise and consistent way. In particular, the structural performance of steel fibre reinforced concrete is strongly dependent on the fibre orientation and distribution, see e.g. [1-3]. Due to fibre orientation some fibres will work efficiently e.g. aligned in the same direction as the tensile stresses, whereas others will be orientated less efficiently. In the case of conventional SFRC, a random fibre orientation is generally assumed. In some cases, a high amount of steel fibres may be needed to obtain a sufficient tensile strength making the concrete more expensive and difficult to produce and cast.

The potential of combining SCC with steel fibre reinforcement is significant. Due to the flow of SFRSCC the variation in fibre orientation can be significant, see e.g. [4-7]. Fibre orientation leads to significant anisotropy in the strength, which can be unacceptable if the associated variation in strength is not taken into account. In the future, flow simulations may be a helpful tool to plan the casting procedure to produce a preferred fibre orientation with respect to structural performance. If it is possible to control the fibre orientation, steel fibres may be used more efficiently to reduce the traditional reinforcement.

The paper presents results on fibre orientation in a reinforced wall cast with SFRSCC. From an experimental point of view, a long wall trial casting was carried out in connection with the construction of an underpass bridge for a new city bypass. A small part of the wall was simulated using a newly developed numerical tool to simulate the flow of SFRSCC, which includes explicit modelling of the position and orientation of individual steel fibres [8].

EXPERIMENTAL

A wall trial casting was carried out on the 29 March 2012. The wall was 8 m long and inclined 30^0 corresponding to the inclination of the full scale walls. The height and thickness was 1.2 m and 0.4 m, respectively. Reinforcement was applied on both sides with a rebar spacing of 150-175 mm in both directions and a cover layer of 45 mm. SFRSCC with 60 mm long fibres and a steel fibre content of 40 kg per m^3 was applied. The mix design is shown in Table 1.

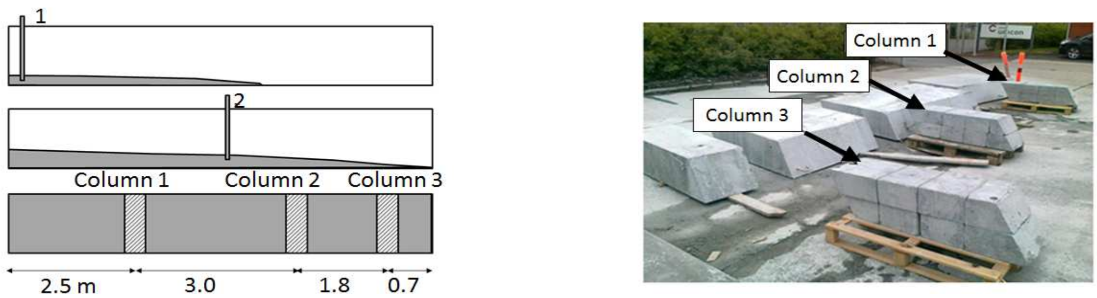
The flow properties were measured using the so-called 4C-Rheometer, an alternative to more classical rheometers [9]. The 4C-Rheometer applies a dry sand blast glass plate to obtain a no-slip condition for more accurate measurement of the yield stress and plastic viscosity. Therefore, the slump flow is often lower compared to the manually operated slump flow measurement according to EN-206-9, which in this case gave 550 mm. This type of SCC is considered a relative stiff SCC, but qualitatively it flowed nicely and form filling was not a problem in this type of application.

Table 1. Mix design (chemical admixtures not shown) and measured flow properties.

	CEM I 42,5N	Fly ash	Micro-silica	Effective Water	Aggregate 0/2	Aggregate 5/8	Aggregate 8/16	Dramix 4D
kg per m^3	350	94.5	26.3	156	690	236	236	40
4C-Rheometer	Yield stress	122 Pa	Plastic viscosity	90 Pa·s	Slump flow	500 mm		
Slump flow (EN-206-9)					Slump flow	550 mm		

The casting was carried out as shown in Figure 1 to the left. The casting shifted between two fixed positions. The casting started at position 1 and the concrete was allowed to flow approximately 6 m before moving the inlet to position 2. Hereafter the inlet position shifted between 1 and 2 when the layer thickness was increased by approximately 0.15 m. The inlet was kept approximately 0.10 m below the concrete surface until a height of approximately 1.0 m was reached. Afterwards, the inlet was moved in a more random way back and forth to complete the filling.

Figure 1. Schematic drawing of the wall casting procedure (left). Cut columns (right).

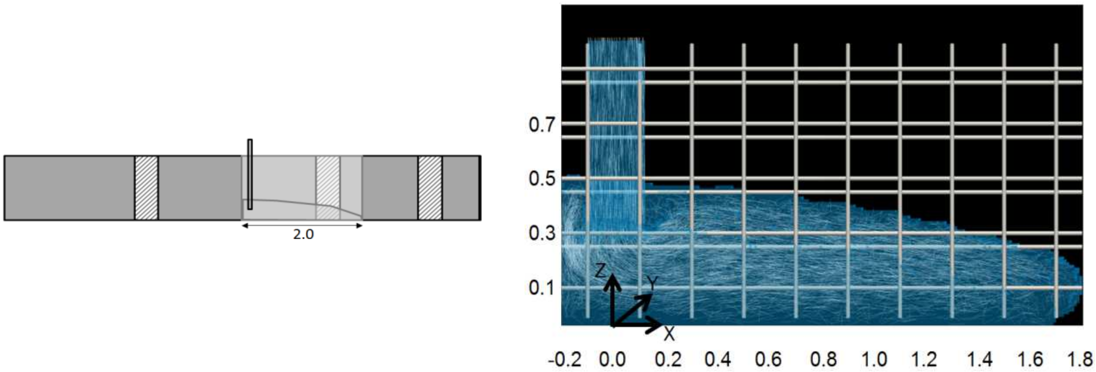


The casting lasted 20 min corresponding to a casting rate of 12 m^3/h. For a structure of this size it can be quite difficult and time consuming to obtain information on fibre orientation. Therefore, it was decided to focus on three locations each representing a region with expected different flow patterns and fibre orientation. Three columns were cut out of the structure and split into sections to enable fibre counting in three directions. The fibre count refer to the number of fibres per unit area in a cross section. Assuming a constant fibre volume fraction, the fibre counts relate to fibre orientation following the well known equation by Krenchel [10]. It introduces an orientation factor varying from 0.0 to 1.0 referring to a uniform alignment of all fibres parallel and orthogonal to the cross-section, respectively. The orientation factor is 0.5 for a perfect 3D random orientation. For the used fibre type and volume fraction, uniform alignment of all fibres orthogonal to the cross section and 3D random orientation of fibres correspond to fibre counts of 7471 and 3735, respectively.

SIMULATION

As the computing times of 3D simulations are quite high, only a smaller part of the wall was simulated. The simulation focuses on a 2 m long section next to the second inlet position as shown Figure 2 to the left. It is assumed that the simulation is only representative of the flow in the trial casting up to the point when the simulated concrete surface reaches the end wall. Hereafter, the flow pattern changes significantly especially as the inlet in the simulation was fixed at 0.3 m above the bottom. In the trial casting, the concrete was cast in layers, and it is assumed that the concrete in the bottom part is not affected when the concrete height increases.

Figure 2. Location of wall simulation with respect to the trial casting (left). View of simulation at the point when the free surface reaches the end wall (right).



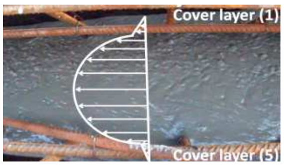
The simulation assumes two phases - a fluid phase and a rigid phase (fibres). The fluid phase is modelled as a Bingham material and represents the concrete without fibres. The yield stress and plastic viscosity applied in the simulation were based on measurements on concrete batches without fibres tested during the development of the final concrete with fibres. It was found that the slump flow decreased by approximately 50-100 mm when fibres were added to the concrete. In this case, it was decided to apply a yield stress of 70 Pa corresponding to a slump flow of 560 mm applying the 4C-Rheometer. Also, the plastic viscosity increases when adding fibres, and it was decided to apply a plastic viscosity of 30 Pa·s for the concrete without fibres.

Finally, some assumptions were made regarding the filling rate and the number of fibres. A high filling rate of 100 m^3/h was chosen to speed up the simulation. Further studies are needed to study the effect of filling rate in more detail. In particular, the effect of the filling rate on the shear pattern and the formation of plug flow zones. For now, it is assumed that the overall shear pattern in the simulation is similar to that in the trial casting. The number of fibres has a significant effect on the number of computations. Therefore, it was decided to reduce the fibre volume fraction from 0.50 to 0.20 vol%. When comparing simulated and measured fibre counts, this was accounted for by multiplying the simulated fibre count with a correction factor of 0.5/0.2.

RESULTS AND DISCUSSION

Figures 4 and 5 show the measured and simulated fibre counts in the x-, y-, and z-direction. Pictures show the location of the faces, which the fibre counts refer to. In the x-direction the experimental results show an increase in fibre count from the cover layer zones (1 and 5) toward the center and almost no variation over the height, which is most likely because the concrete was cast in layers. The fibre count in the center indicates almost complete alignment in the x-direction whereas the fibre orientation is close to 3D random in the cover layer zones. Observing the flow during casting clearly showed that the concrete flow mainly takes place between the reinforcement grids and in the longitudinal direction. This create a shear pattern which aligns the fibres in the x-direction (Fig. 3).

Figure 3. Observed flow pattern in x-direction during casting.



Also, symmetry across the center of the cross section is observed, which indicates that the inclination of the wall has no effect on fibre orientation. The simulation gives similar results. The same trend is observed from the cover layer toward the center of the cross section, though not as pronounced as in the experiment. An explanation for this has not been found yet but one reason may be the reduced fibre volume fraction applied in the simulation. At higher volume fractions, fibres may tend to bridge and make it more difficult for fibres to penetrate into the cover layer zone. In the simulation, fibre counts seem to decrease for increasing x, which may be attributed to the fact that some of the fibres get caught as they pass the reinforcement. The lowest values are found at x=1.6, which may also be attributed to the fact that this position is close to the free surface where fibres tend to align in the same direction as the free surface. Thus, the sections from x=0.6-1.4 seem the most representative of the trial casting and overall the simulation correlates quite well with the measured fibre counts. In the y-direction the experimental results show significantly lower fibre counts compared to the x-direction. Like in the x-direction, the variation over the height is not significant. The simulation confirms the observed lower fibre counts relative to the x-direction, but compared to the experiment fibre counts are lower by a factor of three. An explanation for this discrepancy has not been found, and further studies will investigate it. In the z-direction the experimental results show the lowest fibre counts compared to the x- and y-direction. The fibre counts are approximately half of that of 3D random and there is no variation over the height. The simulation shows a similar trend and values are close to measured values. The results are shown for z=0.2, but for high x-values this is close to the maximum height of the simulated concrete, which is why some values are zero.

Figure 4. Measured (left) and simulated (right) fibre counts in the x and y-direction. Location of fibre count faces (top). Dotted lines represent orientation factors of 0.5 and 1.

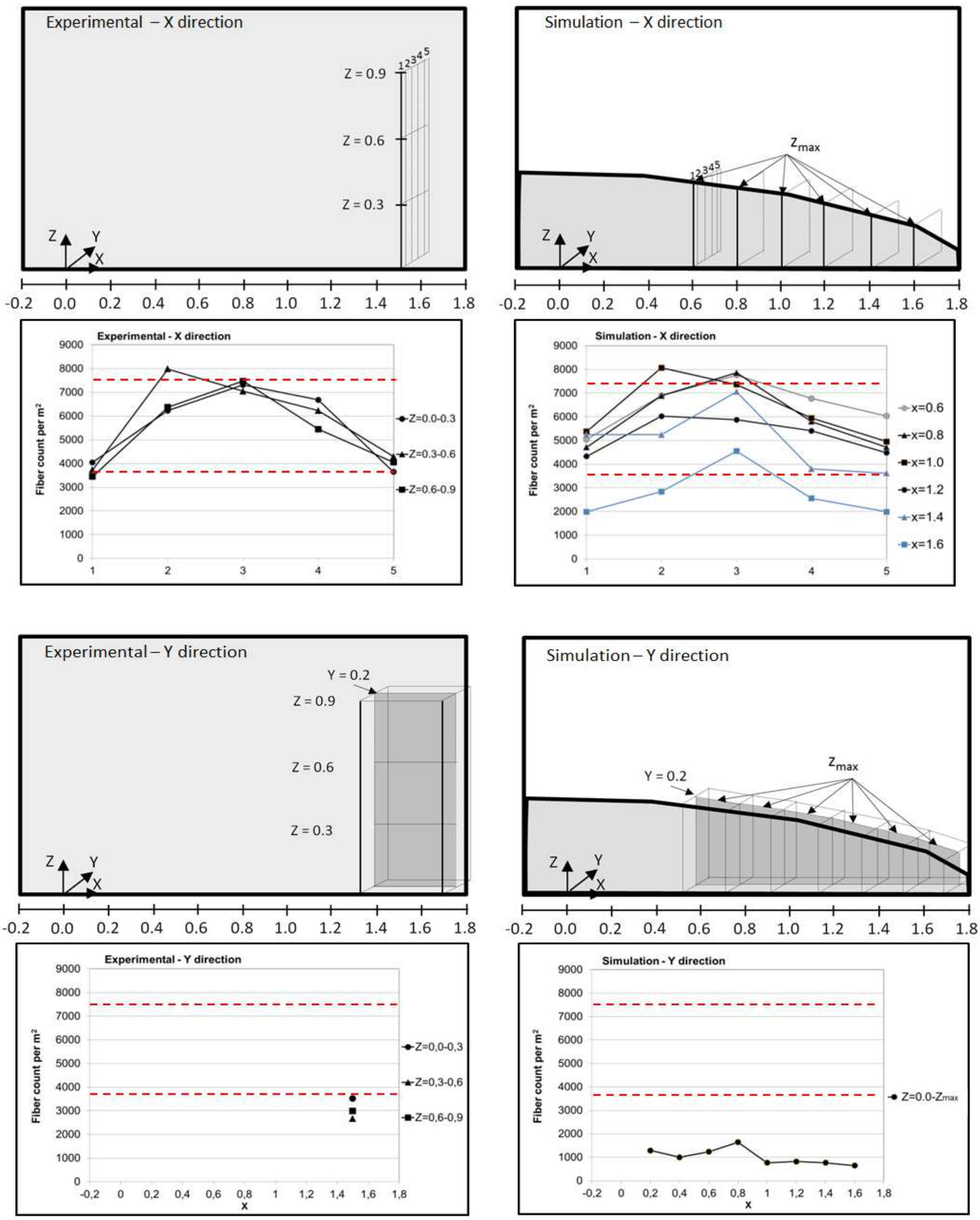
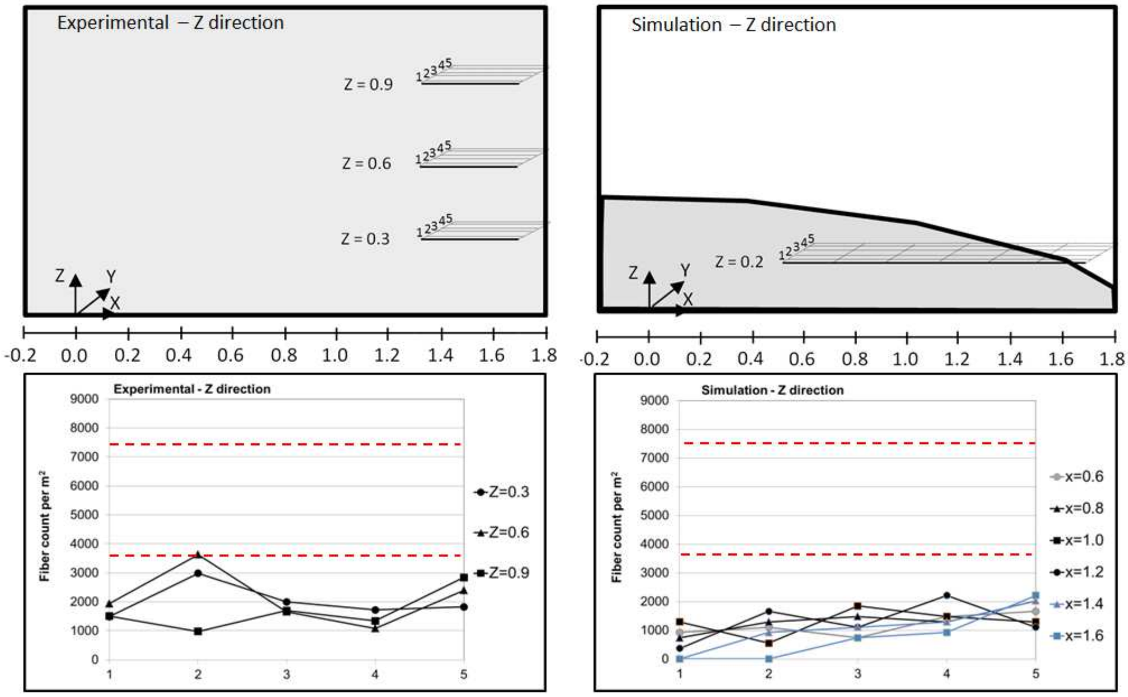


Figure 5. Measured (left) and simulated (right) fibre counts in the z-direction. Location of fibre count faces (top). Dotted lines represent orientation factors of 0.5 and 1.



CONCLUSION

This paper has studied 3D fibre orientation of SFRSCC in a reinforced wall based on fibre counts. Simulated and measured fibre counts were compared in three directions. Considering natural variations in trial castings of this size and the assumptions applied in the simulation (reduced wall length and fibre volume fraction, fixed inlet, higher casting rate, rheological properties), simulations show overall agreement with the experimental findings. The results show a strong alignment of fibres in the longitudinal flow direction. Free flow in the longitudinal direction results in almost perfectly aligned fibres in the center of the wall. In the cover layer zones fibre orientation is reduced and closer to 3D random. The results presented have assumed a homogeneous distribution of fibres i.e. fibre counts are directly related to fibre orientation. Further studies will be carried out to verify this assumption. Studies will also look into simulations applying a continuously moved inlet position just below the concrete surface and increased fibre volume fractions in order to compare simulations to the remaining two columns. In the future, further development and verification of tools to simulate the flow of SFRSCC may help to provide structural designers with the necessary confidence to prepare structural designs where fibre orientation is taking into account in a rational, precise and consistent way.

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