Discrete Element Simulation of the Fresh State Steel Fiber Reinforced Self-compacting Concrete

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Abstract. The distribution and orientation of fibers in Steel Fiber Reinforcement Self-Compacting Concrete (SFRSCC) are paramount given its influence in the mechanical properties of the material/structural elements.

A two-way coupled model based on Discrete Element Method (DEM) to simulate the flow of clumps of particles with the high aspect ratio as fibers and two-phase particles as concrete is developed and introduced briefly in this paper. The framework is capable of modelling of the movement (translation and rotation) including the separation and contact detection of the particles. The interaction of the particles is treated as a dynamic process with a developing state of equilibrium whenever the internal forces are in balance. Newton's laws of motion provide the fundamental relationship between particle motion and the forces causing that motion.

Several experiments were conducted and analyzed by means of the inductive test method (a non-destructive method to assess steel fiber content and orientation). Orientation numbers coming from the inductive test method were compared with the simulation to verify the ability of the model to properly represent the flow of the fresh state SFRSCC. Through comparison with the experimental data, it is shown that the numerical model predicts the final distribution and orientation of the fibers sufficiently accurate and in a reasonable amount of time. The results obtained represent a step forward, showing that it is possible to apply advanced numerical tools for a preliminary assessment of the performance of SFRSCC, which might have positive implications through improved reliability of the design procedures.

Keywords: Steel Fiber Reinforcement Self-Compacting Concrete · DEM Simulation · Orientation and Distribution of the Fibers

1 Introduction

Steel fiber reinforced self-compacting concrete (SFRSCC) is a type of cementitious composite construction material that emerged recently [1, 2]. Since SFRSCC is a complex material, its composition makes it extremely difficult to predict the final

detailed behavior of structural elements. It cannot be assumed to be an isotropic material any more since the fibers orient and disperse during the flow. The knowledge of final orientation and distribution of fibers in the structural elements could provide a basis for understanding how the fibers influence the final mechanical properties of the structural elements [3].

Experimental work leading to the knowledge of orientation and distribution of fibers is often a very time and resource consuming procedure. At first, someone has to do the casting of the elements. The cast element has to be left to harden, cut into pieces and only then a computational tomography (CT) scanner can be used to obtain the 3D image of the fibers in the elements. However, only small parts of the elements can be CT scanned due to the fast overheating of the device [4]. An alternative method to assess the fiber content and orientation in SFRC element is inductive method. Despite several advantages, it only gives average values without providing any information on the scatter or probabilistic distribution of the fiber orientation [5]. A completely different approach might be to use a transparent yield stress fluid such as Carbopol [6] to replace the fluid matrix of self-compacting concrete. All these approaches are not simple and, therefore, only a limited amount of information is obtained from such experiments. On the other hand, numerical simulations are limited only by the computational power. A simulation tool capable of simulating a flow of self-compacting concrete together with fibers and the largest aggregates could provide a sufficient alternative for obtaining the required information.

The objective of this study is to propose and validate a numerical approach for the simulation of the casting process of SFRSCC in fresh state. For this subject, a set of constitutive laws that represents the interaction of particles (aggregates) surrounded by a layer of cement paste and clumps of particles as high aspect ratio steel fibers in fresh state self-compacting concrete is proposed. Then an experimental program related to the casting process of the SFRSCC in was conducted. Finally, calibration of the constitutive law with the experimental results are performed.

2 Applications

Any simulation tool should be validated preferably against both analytical solutions and as many experiments as possible. One of the main objectives of this study is to show the capability of the model to properly describe the complex behavior of steel fiber orientation and distribution in the self-compacting concrete. To do so, the orientation of fibers as a result of the simulation model is compared with the orientation of fibers in the real experiment.

3 Experimental Investigation

The production and characterization of the SFRSCC was performed at the Laboratory of Technology of Structures Luis Agulló (UPC). Six cubic sample compositions with the dimension of 15 cm were defined and produced (see Fig. 1). The compositions used were selected in order to reproduce those typically found in practice. After the

production, inductive test was conducted to evaluate the fiber orientation of the mixes. The material composition and the notation used to refer each element is detailed in Table 1.
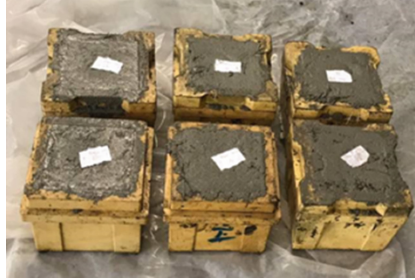

Fig. 1. Casting of the cubic elements

Table 1. Material composition and notation used to refer each element.

Components	Characteristics	Content (kg/m^3)		
Cement	CEM II 42.5R	425		
Sand 0–5 mm	Granite	1325		
Sand 5–10 mm	Granite	150		
Gravel 10–20 mm	Granite	250		
Water		200		
Superplasticizer	Pozzolith 7003	4.5		
Hydration activator	Master paste 3850	5.85	6.75	7.95
Fibers	Steel fiber	60	90	120
Reference code		C1A, C1B	C2A, C2B	C3A, C3B

3.1 Test Method

To evaluate the orientation of the steel fibers, the "inductive test method" [7] improved by Cavalaro et al. [8] has been used. The inductive test method allows assessing the amount and orientation of steel fibers in cubic specimens. The method is based on the ferromagnetic properties of the steel fibers that are able to alter the magnetic field around them. Therefore, if an inductive coil acting as a sensor is placed wrapping the specimen, the fibers will affect the inductance of the sensor. An increase of the inductance occurs when the fibers are located in a position parallel to the direction of the magnetic field (parallel to the axis of the coil), whereas those located in a per-pendicular direction cause practically no variation [9].

The testing procedure for a cubic specimen is very simple: the cubic specimen is located on a non metallic surface with the concrete-pouring face upwards (axis Z), for instance. The specimen is then wrapped by the inductance generated by a coil, and the increase of the inductance is measured with an impedance analyzer (see Fig. 2).

The same procedure is repeated with the specimen turned towards the axes Y and X. Cylindrical specimens can also be measured using same technique by spinning the specimen around specific directions. Further information about the method may be found in [10].
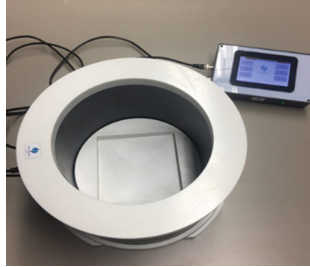

Fig. 2. Equipment of the inductive method: analyzer and cylindrical sensor.

4 Simulation

The method used in this study is a variation of the DEM, which allows the modelling of movement (translation and rotation) including the separation and contact detection of particles [11]. The interaction of the particles is treated as a dynamic process with a developing state of equilibrium whenever the internal forces are in balance. A general particle-flow model simulates the mechanical behavior of a collection of arbitrarily shaped particles in a system. The term particle denotes a body that occupies a finite amount of space and are assumed to be rigid. Hence, the mechanical behavior of such a system is described in terms of the movement of each particle and the inter-particle forces acting at each contact point. Newton's laws of motion provide the fundamental relationship between particle motion and the forces causing that motion.

4.1 Concrete Particle Definition

In general, DEM that are capable of simulating the flow analysis of a concrete mixture can be divided into three main sub groups [12] as shown in Fig. 3.

- Single-phase element model, (see Fig. 3-a). The mixture is considered to be the concrete as a single-phase material, represented by the assembly of spherical elements.
- Separate single-phase element model, (see Fig. 3-b). The mixture is divided into a mortar phase and an aggregate phase, represented by a combination of separate single-phase elements as mortar and aggregate.
- Two-phase element model, (see Fig. 3-c). The mixture is divided into a mortar phase and an aggregate phase, represented by the assembly of the two-phase elements consisting of the inner core as aggregate covered with a layer of the mortar.
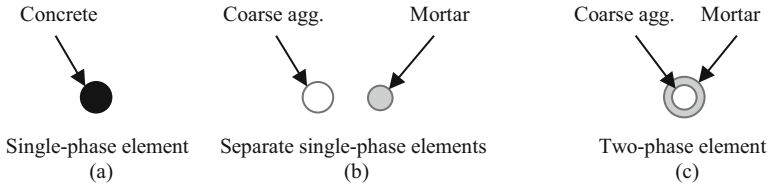
Fig. 3. The discrete element models for a concrete mixture: (a) single-phase model; (b) separate single-phase model; (c) two-phase model.

A two-phase element model is used in this study to represent not only coarse aggregates, but a layer of cement paste or fine mortar covering them as well. Although more complex models are also possible to simulate the real shape, a two-phase element model is suitable due to the high accuracy and the medium computational cost required to evaluate the contact between fiber elements and concrete elements. In fact, using more advanced models could impose unnecessary calculation time, which would not add significant value on the results.

4.2   Fiber Definition

Steel fibers may be defined as a clump of 131 separate spherical particles (see Fig. 4). This number balances the accuracy and the computation cost. The fiber selected for the simulation is a double hooked-end steel fiber, which was also used in the experimental program. The properties of the fiber are presented in Table 2.
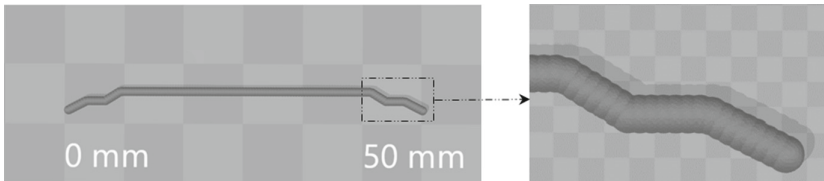

Fig. 4. Numerical simulation of 4D steel fiber consist of 131 spherical elements.

Table 2. Properties of 4D steel fiber.

Shape	Double Hooked 4D
Length	60 mm
Diameter	0.75
Aspect ratio	80
Tensile strength	1,800 N/mm^2

4.3 Rheological Model

The constitutive relations are developed in order to describe the interactions between two neighboring particles and clumps in simulating fresh state SFRSCC. The normal and tangential components of the contact force reflect the different types of interaction amongst the particles. The normal component represents the state of the contact, compression or tension mode, and gives quantitative information about the normal force. This component of the force is active throughout the entire simulation, even if the material does not move, here compression under gravitational force. The tangential component of the force represents the effect of the friction and begins acting when the particles start to move. Then both force components are acting simultaneously.

Studies from other authors [13] showed that the motion of the fresh state self-compacting concrete in the normal direction has elastic and viscous components working simultaneously. The Kelvin rheological model is generally used to represent this condition. This model is composed by an ideal spring arranged in parallel to a dashpot. The spring accounts for the elastic behavior of the mortar whereas the dashpot accounts for the effect of its viscosity.

Although there is a scarce amount of studies in the field of simulation of fiber elements in the DEM, the author suggested to use Bingham rheological model in the normal direction. The Bingham model consists of a Saint Venant element and a dashpot connected in parallel. The deformation of this model is not possible before reaching the yield stress. When the yield stress is achieved, the model exhibits visco-plastic deformation. A complete list of simulated interactions in normal and tangential direction are presented in Table 3.

Table 3. Interaction between elements in normal and tangential direction.
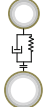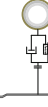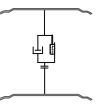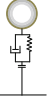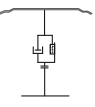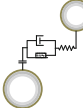

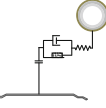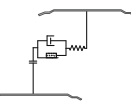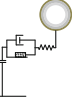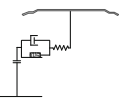|	Contact Type	Ball-Ball	Ball-Clump	Clump-Clump	Ball-Wall	Clump-Wall
Normal Direction	Schematic Drawing					
	Contact Model	Kelvin	Bingham	Bingham	Kelvin	Bingham
	Key Parameters	k_n, C_n	$C_n, bond_n$	$C_n, bond_n$	k_n, C_n	$C_n, bond_n$
Tangential Direction	Schematic Drawing					
	Contact Model	Bingham-Hook	Bingham-Hook	Bingham-Hook	Bingham-Hook	Bingham-Hook
	Key Parameters	$k_s, C_s, bond_s$	$k_s, C_s, bond_s$	$k_s, C_s, bond_s$	$k_s, C_s, bond_s$	$k_s, C_s, bond_s$

Figure 5 shows schematically the force–displacement relation between two concrete elements as introduced for the contact model in the normal direction. Based on this model, the inter-element interaction can be generally divided into six different zones.
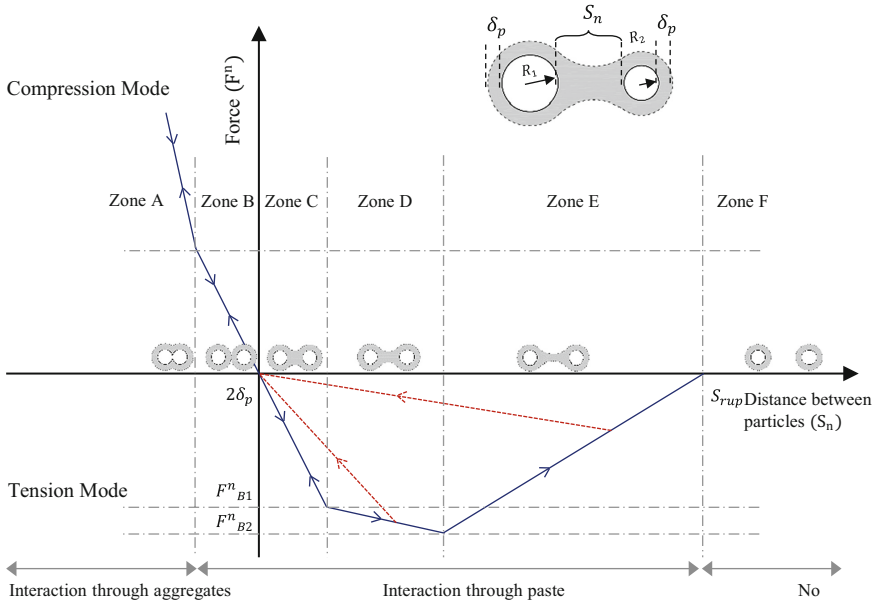
Fig. 5. The interaction force (F^n) - distance (S_n) plot between two discrete elements in normal direction. δ_p and S_{rup} are the thickness of the paste layer and rupture distance, respectively.

In zone A, in which the inter-particle distance $S_n < 0$, the inner phases of elements are in direct contact. In zone B, in which the inter-particle distance varies between zero and the sum of the two paste layer thicknesses around each particle $0 < S_n < 2\delta_p$, the interaction happens through contact between paste layers. In zone C, D and E with $2\delta_p \leq S_n < S_{rup}$, the cohesion force due to the presence of the paste bridge decreases by gradually increasing the inter-particle distance. In zone F, with $S_n \geq S_{rup}$, two particles are completely separated and there is no interaction between them anymore. The other parameters, i.e. F^n_{B1}, F^n_{B2}, which depend on the size of particles and paste consistency, can be obtained from the force-distance formula.

In tangential direction, the elastic-plastic behavior is considered where the elastic behavior is restricted by the Coulomb criterion ($\left|F^t_{max}\right| = \mu \left|F^n\right|$). μ (frictional coefficient) is considered equal to 0.7 and 0.5 for inside phases contact and outside phases contact, respectively.

5   Results

This section presents results obtained by inductive test method. These experimental results are then compared to results obtained from their respective numerical simulations. The following section studies the average orientation of the steel fibers in each direction by the means of the orientation number.

The casting process of the cubic specimen was simulated using ITASCA Particle flow code (PFC) [14] and the interaction model described in the previous section. The formwork of the cast specimen was modelled using discrete element method. The numerically obtained orientation of the steel fibers was subsequently compared to the experimental results presented in the following section.

Figure 6 shows the resulting distribution of the steel fibers with 60, 90 and 120 kg/m^3 dosage of steel fiber, respectively. The orientation of the steel fibers is depicted as the 3D view of the orientation numbers in x, y and z directions. The steel fibers tend to orient in the regions close to the vertical walls of the formwork, which is primarily caused by the wall effect [15]. It is geometrically impossible to have a rigid fiber located normal to the formwork at a distance less than half-length of the fiber. Hence, the rigid fiber tends to orient according to the surrounding flow with a restriction imposed by the wall. In the bulk of the specimen, the steel fibers remain in a more or less random orientation state in x and y direction due to the shear induced orientation and the extensional stress induced orientation [16].
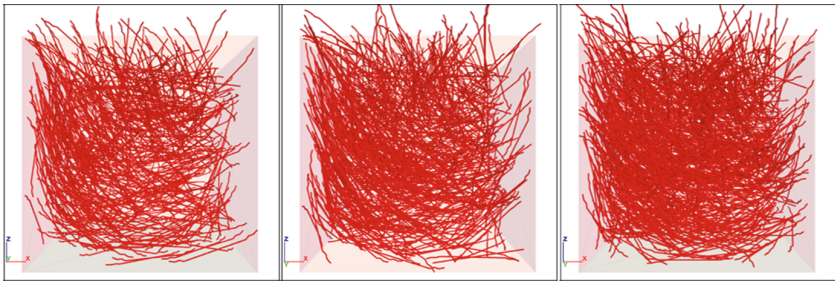

Fig. 6. Representation of the orientation of fibers inside the cubic mold. Fiber dosage: a) 60 kg/m^3 b) 90 kg/m^3 c) 120 kg/m^3

Table 4 presents a comparison of the orientation numbers in each direction obtained from the simulation and the inductive test experiment. There seems to be a direct correlation between the results from the experimental study and the simulation in each direction. The orientation of fibers in individual regions is represented by means of second order orientation tensors [16]. The orientation tensors were visualized in the form 3D ellipsoids and in this paper in the form of 2D ellipses (see Fig. 7). The orientation of the ellipses represents the mean orientation of fibers in the region. Aspect ratio of the ellipses represents the alignment of fibers in the region. High aspect ratio of the ellipses corresponds to a high alignment of the fibers and the circular shape of the ellipses corresponds to a uniformly random orientation of fibers.

The main outcome of the experiment was a set of 3D ellipsoids representing the orientation of fibers in the cubic element. Figure 7 presents top views and side views of the elements with orientation ellipses result from both numerical simulation and inductive test analysis. The fibers tend to orient normal to the flow direction which forms a circular pattern. The longer the distance from the inlet the more the orientation of fibers increase. Due to the limited size of the element, the fibers seem to be more

randomly distributed in the x-y direction. A reasonable explanation might be a boundary effect as described in [17]. An apparent Navier's slip [18] occurred during the experiment and simulation.

Table 4. Comparison of the simulated fiber orientation number with experimental results.

Reference code	Exp	Num	Error	Exp	Num	Error	Exp	Num	Error
	$\cos(\theta_x)$			$\cos(\theta_y)$			$\cos(\theta_z)$		
C1-A	0.5098	0.534	4.70%	0.5082	0.5206	2.40%	0.4611	0.4587	0.50%
C1-B	0.5316		0.40%	0.5262		1.10%	0.4151		10.50%
C2-A	0.5222	0.5256	0.70%	0.5373	0.5646	5.10%	0.4126	0.4249	3.00%
C2-B	0.5234		0.40%	0.5334		5.80%	0.4161		2.10%
C3-A	0.5482	0.5778	5.40%	0.537	0.5476	2.00%	0.3798	0.3643	4.10%
C3-B	0.5385		7.30%	0.5437		0.70%	0.3838		5.10%

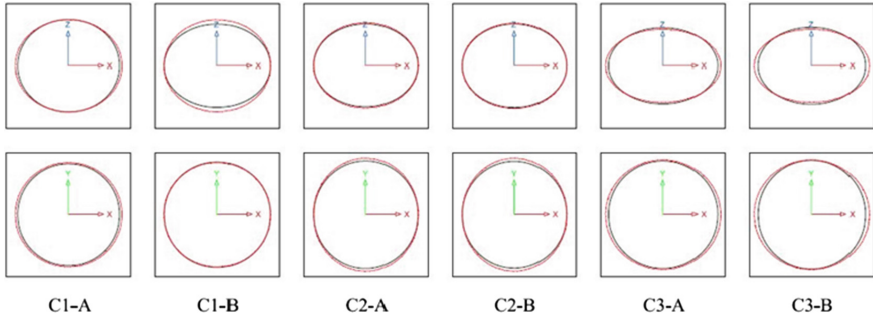| C1-A | C1-B | C2-A | C2-B | C3-A | C3-B |

Fig. 7. Graphical comparison of the fibers in each specimen. Red dashed-lines are representing numerical values and black solid-lines are representing experimental values.

6   Conclusion

The work presented in this paper involves the combined use of experiments and numerical modelling techniques to investigate an important aspect of the steel fiber reinforced self-compacting concrete. The good fit obtained between numerical and experimental results confirm the model and the constitutive law reproduce the fresh state behavior of the SFRSCC in the casting procedure. The results obtained represent a step forward, showing that it is possible to apply advanced numerical tools for a preliminary assessment of the performance of fiber reinforced concrete, which might have positive implications through improved reliability of the design procedures. The proposed use of discrete element method simulations to determine fiber coordinates within cast self-compacting concrete is a novel means for connecting methods of processing to the mechanical performance of fiber reinforced cement composites.

The ability to simulate the casting process of steel fiber reinforced self-compacting concrete, including the movement of individual fibers, has profound implications toward the effective use of these materials within the civil infrastructure. As an important aspect, the results of such flow simulations can serve as input to mechanical models of material behavior. Together with physical experimentation, this coupled simulation of concrete casting presents opportunities for improving material performance for both ordinary and high-performance applications.

Moreover, the framework can be used to approach the material in a more general way and to investigate and understand the other underlying processes of the casting process such as segregation of the fibers and aggregates in a suspension, blocking of fibers behind reinforcement, and Influence of formwork surface on the orientation of the fibers.

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